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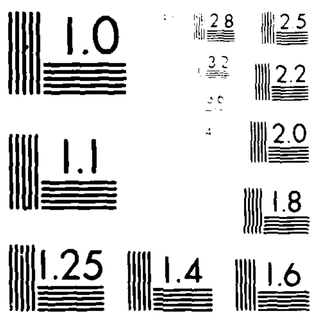

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HIGH-PERFORMANCE AUXILIARY POWER UNIT TECHNOLOGY DEMONSTRATOR

Avco Lycoming Stratford Division
550 South Main Street
Stratford, Connecticut 06497

December 1980

Final Report for Period July 1977 - July 1980

Approved for Public Release, Distribution Unlimited

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The report covers the design, procurement, and testing of two High-Performance Auxiliary Power Units in the 500 shp class. The program demonstrated the ability of the LPU-101-700 power producer, combined with a modified existing APU in an advanced state of development, to meet Air Force minimum requirements of 1.7 hp/lb and 130 hp/cu ft with an sfc of 1.0 lb/hp-hr or less. Two units were successfully subjected to extensive environmental and endurance testing.

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FOREWORD

This report has been prepared by the Avco Lycoming Stratford Division under Air Force Contract F33615-77-C-2015, which was a part of Aircraft Subsystems Technology Program. The power systems task, within this project, was identified as Project 23480401.

The work reported herein was performed during the period 1 July 1977 through 31 July 1980 under the direction of Mr. William Green, HPAPU Project Chief, Avco Lycoming Stratford Division. The Air Force Project Manager was Mr. Everett Lake of the Aero Propulsion Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio.

The report summarizes the design, test, and demonstration of the High Performance Auxiliary Power Unit Technology Demonstrator.

This report contains a general discussion of the hardware, a description of power producers, and addresses the configuration of the HPAPU system.

Acknowledgement is extended to Mr. Paul Letourneau, Group Engineer, Sundstrand Corporation, and Mr. Dave Packard and Mr. James Antell of the Avco Lycoming Engineering Test Department for their contributions in preparing and supervising the input required for the test and demonstration phase of the program.

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SUMMARY

The objectives of the program were to build, test, and deliver two High Performance Auxiliary Power Units (HPAPU). Development work was to be limited to that required to upgrade an existing powerplant and its associated control system to meet performance requirements. The other HPAPU components were to be already developed. These were to be used as test equipment to demonstrate the capability of the power producer. Risk associated with the program was to be kept to a minimum and restricted to the power producer and control.

A modified Avco Lycoming LTS 101-700 engine was chosen to demonstrate high power-to-weight and volume ratios, the basic requirements of the program. The engine is a free-power turbine with an airflow of approximately 5 lb/sec at maximum power. The principal modification required for the HPAPU application was the addition of containment material to guard against tri-hub burst of the high-speed rotating components. Material changes in the gas producer provided improved low-cycle fatigue properties and minor configuration changes to improve performance.

The system chosen to demonstrate power producer capability used existing Sundstrand accessories, with a new adapter gearbox to suit the output speeds and mounting arrangement of the power producer. The loading system comprised a load compressor capable of delivering approximately 3.6 lb/sec of air at a pressure ratio of 3.6:1 and a 12,000 rpm generator rated at 75kva. Combined with accessory loading and gearbox losses, the load imposed on the power producer at maximum conditions was approximately 500 shaft horsepower at standard-day conditions.

The program was conducted in three phases:

Phase I - Preliminary Design

Phase II - Detailed Design

Phase III - Test and Demonstration

Phase I was started in July 1978 and completed in December 1978. Phase II comprising detailed design of the HPAPU, layout of the necessary test facility at Sundstrand, and preparation of environmental and endurance test plans was completed in May 1979.

Phase III of the program involved the procurement and assembly of HPAPU details and test equipment and performance of the test programs prepared and submitted during Phase II. All testing was completed in April 1980, with the HPAPU meeting or exceeding all the performance requirements of the Air Force contract.

The test program was divided into two sections. Environmental testing on the first HPAPU power producer was conducted at Avco. The unit demonstrated successful sea level starting at ambient temperature and cold-day and hot-day temperatures of -70° and 130°F, respectively.

Peak power of the power producer, predicted to be 456 shaft horsepower at 130°F, was demonstrated at this point for 10 hours, at temperatures ranging between 130° and 135°F.

Successful starts were accomplished at altitude conditions representing 10,000, 20,000, and 25,000 feet.

The power producer assembled to the first HPAPU system performed a series of ten simulated main engine starts on a Sundstrand test rig. This rig represents the inertia characteristics of a Pratt and Whitney F100 turbofan engine.

The second HPAPU was endurance tested at the Sundstrand facility. The procedure called for 100 hours of endurance running, comprising of 50 hours of cyclic operation and 50 hours continuous operation at peak power. Continuous operation was interrupted once because of a fault in facility instrumentation wiring. Cyclic operation represented the full range of pneumatic and electrical loads and transients; one simulated main engine start was performed in each one-hour cycle.

Upon completion of endurance testing, the second system was used in a formal demonstration of the capability of the HPAPU to government, aircraft, manufacturing, and airline representatives.

Before delivery of the systems to the Air Force, both power producers were disassembled for inspection. There was foreign object damage in the compressor section of the power producer from the first HPAPU. The axial compressor and diffuser were replaced. Remaining discrepancies on both power producers were minor. The two systems were rebuilt, tested, and shipped.

In conclusion, the Avco Lycoming power producer used in the HPAPU demonstration program met or exceeded all of the required performance goals and satisfied the Air Force objective of proving that the demonstrated technology is suitable for immediate application to military aircraft.

SECTION I

INTRODUCTION

The U.S. Air Force awarded a High Performance Auxiliary Power Unit (HPAPU) Technology Demonstrator contract to Avco Lycoming in July 1977. Under the contract, the program's objectives were to demonstrate an HPAPU in the 200 to 500 horsepower class with a power-to-volume ratio of at least 130 hp/ft^3 and a power-to-weight ratio of at least 1.7 hp/lb.

Performance of auxiliary power units at the time of the contract award was below that available from component technology already developed. Aircraft designers were reluctant to call for a system with components that were not demonstrated to be reliable and maintainable. Recognizing the need to demonstrate these characteristics, the Air Force sponsored a program for the design, test, and delivery of two HPAPU systems. As program risks were to be kept to a minimum development effort was to be restricted to the power producer and its associated control. Gearbox and driven components were essentially considered support items to the program.

The system's load compressor and generator were to be either in production or at a final stage of development to minimize associated technical risk. The power producer itself was to be developed from an engine which incorporated advanced technology and which had already demonstrated a minimum of 100 operating hours on the advancement features. The power producer selected was a modified LTS 101-700, a free-power turbine in the 5 lb/sec airflow class. The power producer was mounted by means of an adaptor gearbox to an existing Sundstrand accessory gearbox that drives a load compressor and 75 KVA generator (Figure 1) through the power train. A secondary gear train drives the fuel control/pump and the lube pumps. During the start mode the engine was driven by means of an electric starter. This Sundstrand hardware, while not in production, was developed to the stage where any further risk was negligible. An electronic controller connected to the pneumatic/mechanical fuel control, by means of a proportional solenoid, provided the necessary control and system safety functions.

The program was to be conducted in three phases:

Phase I Preliminary Design

Phase II Detailed Design

Phase III Test and Demonstration

Phases I and II were to incorporate required APU safety features into the power producer to optimize its performance for an APU duty cycle, and to match it to the needs of driven hardware. Phase III was to complete the manufacture and procurement of power producer and system details, preparation of dedicated test facilities, and performance of environmental and endurance testing.

On conclusion of the successful test and demonstration program, two complete HPAPU systems, spares, and test support items were to be delivered to the Air Force.

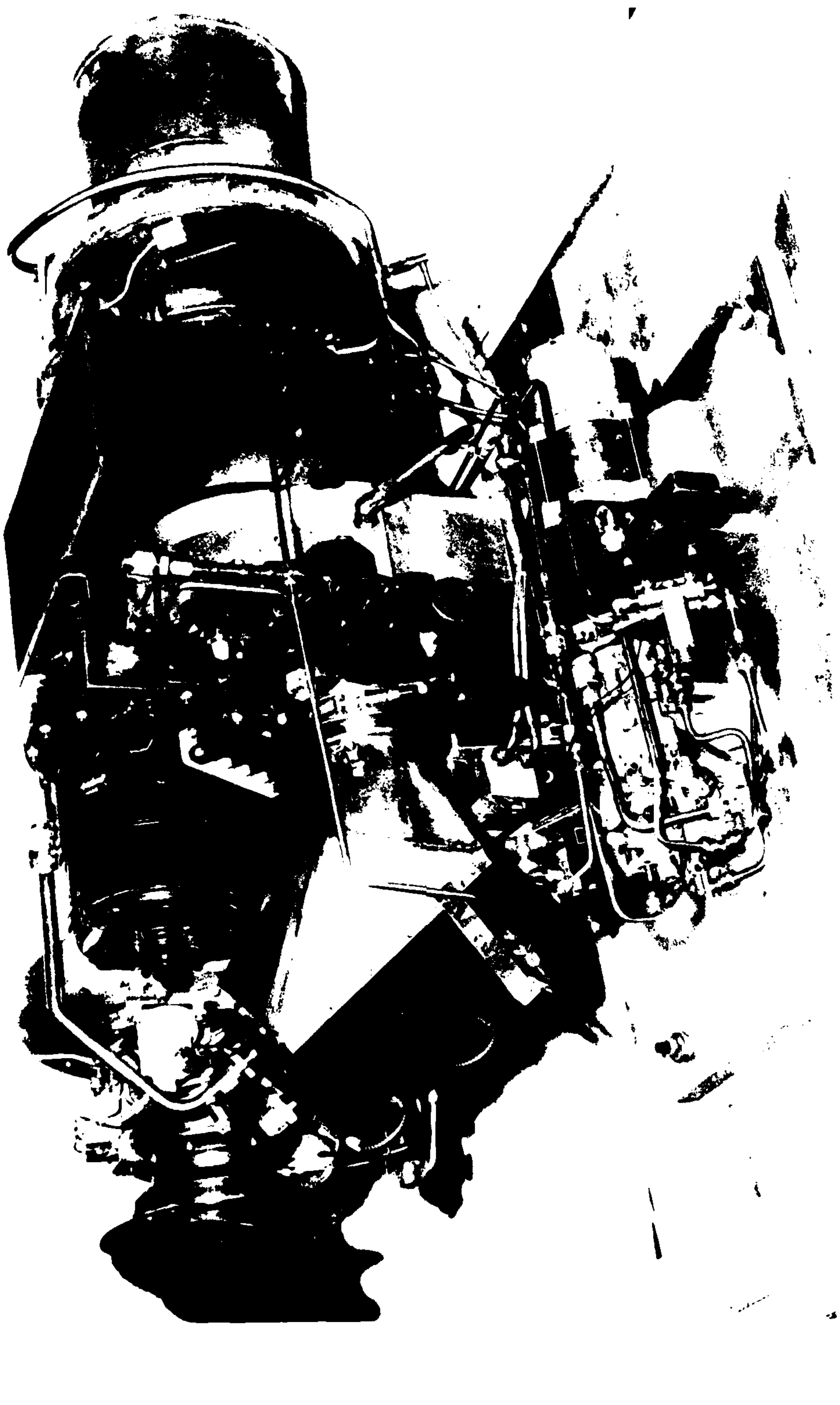


Figure 1. High Performance Auxiliary Power Unit.

SECTION II

DISCUSSION

2.1 BACKGROUND

Phases I and II of the High Performance Auxiliary Power Unit program concentrated on the preliminary and detailed design of the Avco Lycoming LPU 101-700 power producer and the modifications required to be made to an existing Sundstrand APU to adapt it for use with the power producer.

Phase III of the program consisted of the manufacture and procurement of details required for the power producers and HPAPU systems, preparation of dedicated test facilities at Avco Lycoming and Sundstrand, and completion at these facilities of environmental and endurance testing.

2.2 POWER PRODUCER

Power Producer Design Concept

The LPU 101-700 is an advanced technology free-power turbine turboshaft power producer in the 5 lb/sec airflow class wth a peak APU power rating of 456 shaft horsepower at 130°F inlet air. Output power at lower ambient temperature is limited to 500 shaft horsepower. It is approximately 17 inches long and 16 inches diameter, as its maximum, at the compressor outlet.

The power producer consists of an air inlet scroll, and gas generator and power turbine modules. The gas generator module includes a single-stage axial, and a single-stage centrifugal compressor. The power turbine module includes a reverse-flow annular combustor and a single-stage power turbine. Overall, the configuration results in a short, compact, engine.

The flow path through the LPU 101-700 engine is shown in Figure 2. Air enters the inlet scroll in a radial direction and is then turned 90 degrees to enter the compressor. The compressor discharge air is diffused radially and turned 90 degrees into the reverse-flow annular combustor. Primary air and fuel are introduced at the aft end of the combustor. The gas flow leaves the combustor with a 180-degree turn to resume axial flow through the gas generator turbine and power turbine to exhaust.

The inherently low erosion sensitivity of the centrifugal compressor contributes significantly to the ruggedness of the engine. The inlet scroll is manufactured from a fire-resistant, polyimide composite.

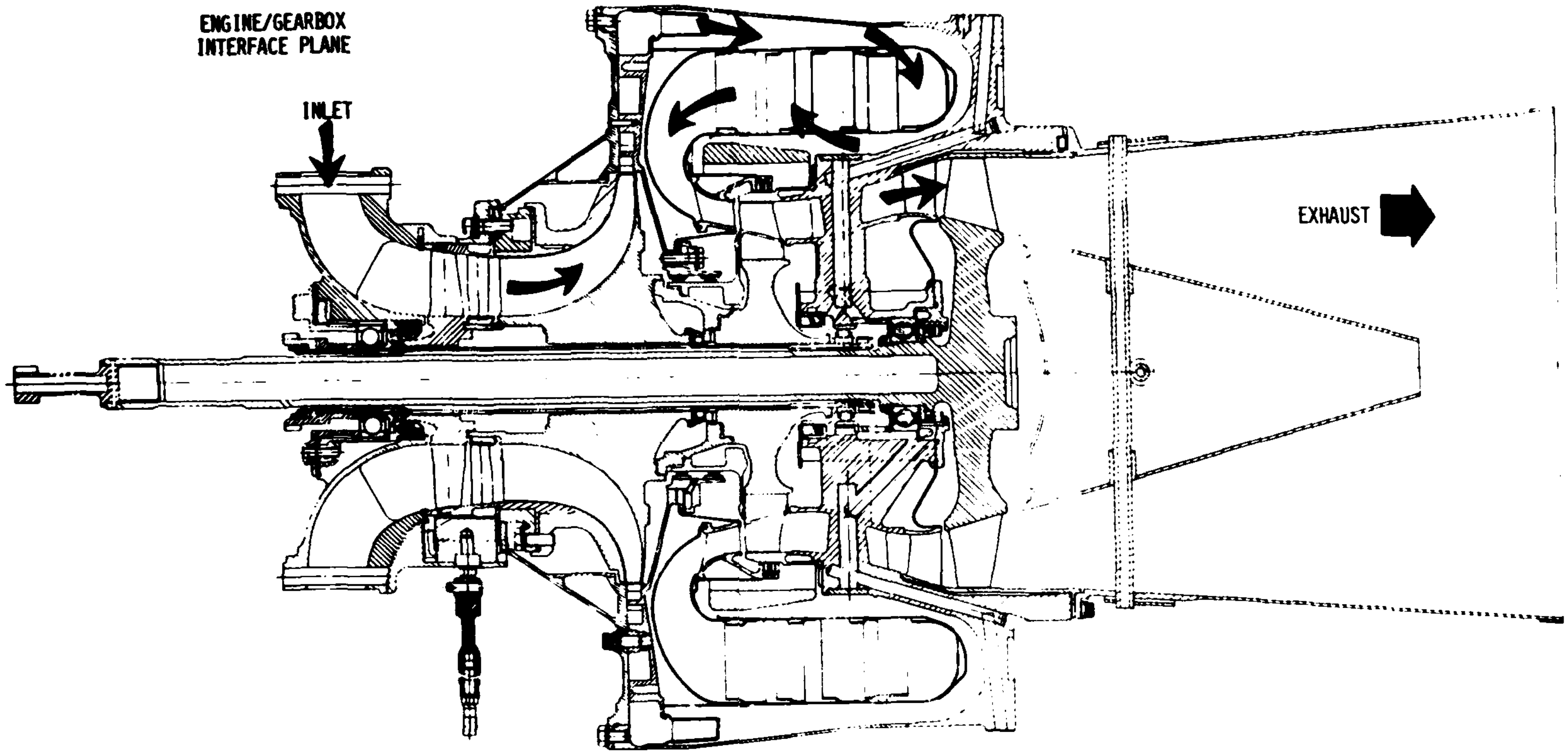


Figure 2. Power Producer.

The reverse-flow annular combustor liner is structurally combined with the rear bearing support housing providing a sturdy support shell. This configuration provides a heat shield which covers the hot engine sections.

The gas generator module and the power turbine module interface is such that when separated, the hot engine section is completely open for easy inspection.

This design concept has yielded an engine that has demonstrated a significant improvement in small engine performance with an accompanying reduction in engine complexity and cost. Significant growth potential has also been designed into the engine in terms of a low initial turbine inlet temperature, thereby ensuring the availability of additional power as the need develops.

Mechanical Arrangement

The power section is constructed of three basic modules: the inlet scroll, the gas generator, and the power turbine module. These modules are identified in Figure 3.

Inlet Scroll

The inlet scroll is a two-piece fire-resistant molded polyimide assembly. It is clamped together around the circumferential flange on either side of the compressor inlet housing by a snap lock. Circumferential positioning is accomplished by a pin in the inlet housing flange.

The scroll is designed with a controlled area distribution with wall and vane curvatures providing the desired airflow distribution into the compressor with low pressure losses.

Gas Generator Module

The gas generator module consists of the inlet housing, the compressor, and the compressor-drive turbine assemblies.

The compressor consists of an axial stage closely coupled to a single centrifugal stage.

The axial stage is a constant-hub converging-tip type of design that has no inlet guide vanes. The rotor of this stage is transonic. An airflow modulation ring located on the outer wall directy forward of the axial rotor is provided for part speed and transient operation. Circumferential slot-casement treatment is located in the wall over the axial rotor tip.

The centrifugal stage is a moderately high-pressure ratio compressor of the radial out-flow type. Diffusion after the impeller is accomplished by means of a channel diffuser and an axial row of deswirl vanes.

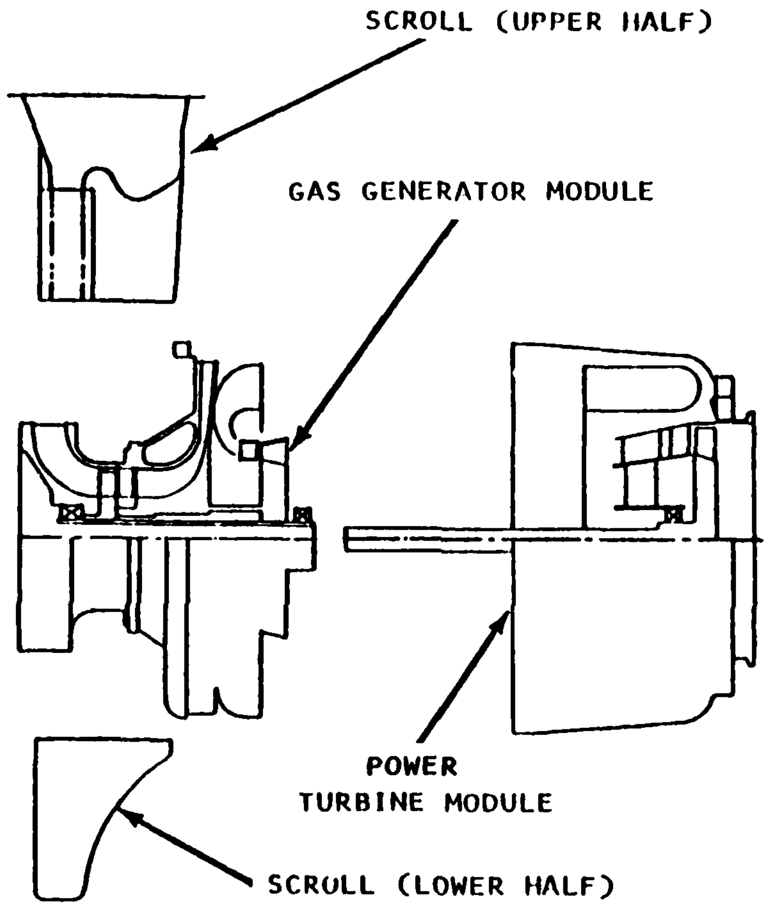


Figure 3. Power Producer Modules.

The inlet and diffuser housings form an integral part of the engine structure and are connected to a gearbox at the front end and the power turbine module at the rear. The inlet housing also supports the forward gas generator shaft bearing with its seal package, and the flow modulator ring and control links.

The cast inlet housing uses four aerodynamic struts to bridge the radial-to-axial flow path channel. These struts accommodate four tie bolts that connect the power producer to the gearbox. The compressor stator vane assembly is inserted into the inlet housing from the aft end, its outer shroud extending forward over the axial compressor rotor, and its flange clamped between the inlet housing and impeller shroud. The vane assembly is split into semi-circular halves to enhance assembly and inspection; its inner shroud forms an interstage seal with the compressor rotor.

An inlet airflow modulation ring is provided to ensure smooth power transients throughout the operating range. The circumferential flow modulator groove and ring are located immediately forward of the compressor vane outer shroud. The ring construction is similar to a piston ring with an eccentric bore. Two tabs on the ring provide attachment points for links connected to a crank mechanism, which, in turn, is connected to a pneumatic actuator bolted to the diffuser flange. The links extend from the ring into grooves cut into the housing. The grooves are angled in such a way that the inside diameter of the ring tends to remain concentric as it is modulated through its operating range.

The diffuser is designed as a two-piece assembly, each piece being investment cast. The diffuser housing forms the forward vertical wall that is machined flat and bolted to the rear half at the vane centers.

The inner flange of the rear diffuser half supports the gas generator nozzle assembly and the stationary outer member of the gas generator labyrinth seal. Trapped and pinched between the nozzle assembly and the diffuser is the combustor curl, which is located radially within a groove in the nozzle inner shroud.

The axial compressor rotor is integrally cast, i.e., the blades and the disc form a single piece. The exit vanes are coined from strip stock and brazed into an inner shroud of the same material and an outer shroud of forged Hastelloy X. The inner shroud is used to provide improved mechanical integrity, while the outer is for tri-hub burst containment of the axial rotor.

The impeller is also cast. A three-piece shroud, made from Hastelloy X forged rings, provides containment for the centrifugal impeller.

The axial rotor and the impeller are clamped against a shoulder at the front end of the gas generator shaft by a nut at the rear of the impeller.

The split stator vane assembly and a split section of the impeller shroud assembly enable the installation of the compressor rotor system without disassembly after balancing.

The turbine wheel is installed on the gas generator shaft by clamping it against the impeller with a nut at the rear of the shaft.

The generator turbine nozzle is an investment casting with integrally cast cooling air passages in the vanes. The cooling air exhausts into the gas stream through slots machined in the positive pressure-side of the vanes. An inner support member of an outer shield and combustor inner curl make up the remainder of the brazed nozzle assembly.

The gas generator turbine wheel is an assembly consisting of a forged disc, insertable blades cast from C103, and a sealing plate with turbine labyrinth seal knife edges.

The gas generator shaft is mounted on two bearings. The forward No. 1 ball bearing, sustaining the thrust load of the system, is a squeeze-film design to minimize the bearing loads and increase rotor stability. The rear No. 2 roller bearing is supported in the power turbine module and lubricated from the power turbine oil system. The single 2 and 3 bearing package minimizes heat rejection. Figure 4 shows a cross section of both the gas producer turbine and power turbine arrangement.

Power Turbine Module

The power turbine module includes a one-piece combustor and rear bearing support housing, the combustor liner, and the power turbine rotor assembly.

The combustor and rear bearing support housing which is an integral part of the engine structure is connected to the diffuser flange of the gas generator module where it provides support for the power turbine and gas generator rotor rear bearings and containment for tri-hub burst of the power turbine rotor. The aft flange is designed to carry the exhaust tailpipe. The investment cast housing uses four aerodynamic struts to bridge the flow path.

The outer flow path wall serves as a support for the gas generator cylinder and is flanged above and in the vicinity of the struts. Aft of the struts, the outer wall is relieved to accept the power turbine nozzle, which is piloted into the housing at the tailpipe flange.

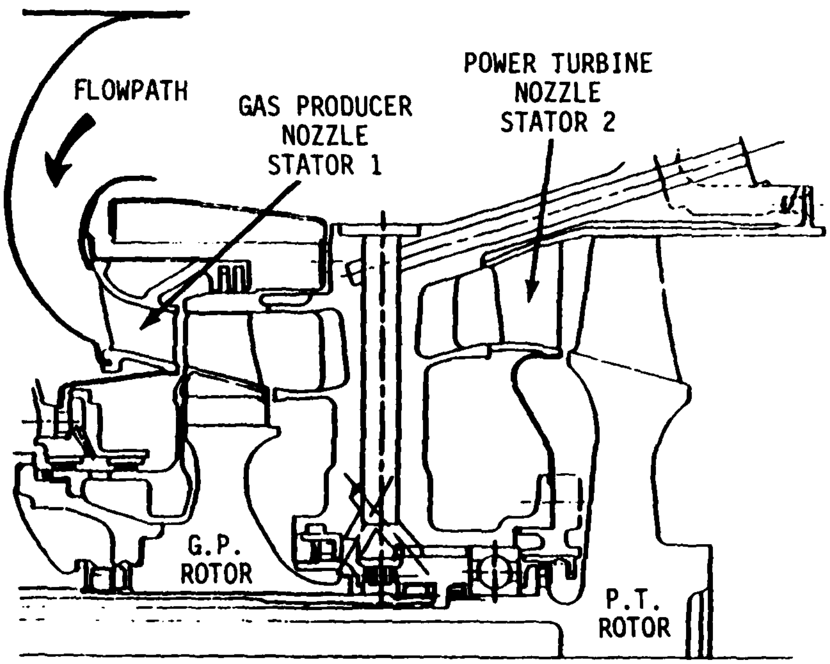


Figure 4. Turbine Cross Section.

Three of the four struts incorporate service tunnels, which in conjunction with drilled bosses along the flow path outer wall, in the combustor annulus, provide access to external pads on the periphery of the housing. Looking forward, the 12 o'clock strut serves as a vent for the gas generator and power turbine bearing cavities; bearing oil feed is at 3 o'clock; and oil scavenge is at 6 o'clock. Between the struts, eight equally spaced bosses are provided for mounting measured gas temperature (MGT) thermocouples to monitor exhaust gas temperature. The thermocouple leads enter through four pads at the rear of the housing.

The outer combustor shell and flange are welded to the outer lip of the casting. The resultant one-piece structure offers the advantage of a minimum number of flanges.

The reverse-flow annular combustor results in a short, lightweight engine. The shortened engine made possible by this design avoids shaft critical speed problems. The combustor and its containment provisions are discussed below in greater detail.

The modular concept is enhanced by having a system that permits removal of the power turbine section without disassembling a connection at the front end of the power turbine shaft. This was accomplished by incorporating a helical spline on the power turbine shaft and the inside diameter of the gear with which it engages. The torsional load reaction of the spline causes the power turbine shaft to screw into the output shaft against a shoulder. The torsional load reaction on the output gear creates an axial force opposing the turbine gas loads and, thus, maintains the bearing load reduction and balancing arrangement.

The power turbine nozzle incorporating uncooled vanes is integrally cast. Its long outer shroud extends rearward, trapped between the rear bearing support housing and the exhaust tailpipe. A spun sheet metal diaphragm, brazed to the nozzle's inner shroud, forms a gas seal with the power turbine seal housing.

The power turbine wheel which is integrally cast and inertia-welded to the shaft is supported at the aft end by a thrust-sustaining ball bearing on the upstream side of the turbine wheel.

The power turbine ball bearing and the flanged gas generator roller bearing are separated by an oil feed ring with two jets impinging on the ball bearing and one on the roller bearing. A second oil jet is provided to the forward side of the roller bearing. The bearing package is sealed by a bellows-type, positive-contact face seal at the aft end.

Combustor

The LPU 101-700 engine uses the same combustor system as all engines of the Lycoming LTS 101 engine family. A reverse-flow, annular combustor (Figure 5) is wrapped around the turbine section, thereby, resulting in a short, light engine without compromising frontal area. Air from the radial diffuser flows axially along the outer liner wall, turns 180 degrees when it enters the primary zone where combustion takes place, and turns 180 degrees again before entering the turbine. Eight dual-orifice pressure atomizing fuel nozzles are used for fuel injection into the primary combustion zone. Two low-tension igniters furnish the spark energy for ignition. No separate starting fuel nozzles are required. Liner wall cooling is accomplished by external convection and internal film cooling.

The significant feature of the combustor aerodynamic design is the unique primary zone flow circulation and air partitioning. The combustion zone essentially has one-sided air admission; and the full annulus height is used for a single recirculation region rather than the two opposed vortices used in conventional designs.

Figure 6 is a schematic of this unique circumferentially stirred flow pattern. The primary air is admitted through slots in the liner header, producing flow circulation about a circumferential mean line. Folding air jets, entering through the inner wall, force the primary zone recirculation. Since these secondary holes exist only on the inner wall, the vortex fills the full annular height of the liner and produces adequate flame stabilization within a smaller cross-sectional space. The folding jet hole pattern is matched to the fuel injector position to ensure recirculation in line with the injector.

Figure 6 shows the flow path of the vortex in the liner. With the folding jet in line with the fuel injector, the initial flow circulation is in a circumferential directon. The vortex is forced to turn to the axial direction on either side of the folding jet. As a result, the mean path of the combustion zone flow vortex takes the shape of a horseshoe centered on the injector and folding jet axial centerline. This flow pattern is repeated around the circumference of the combustor liner for each of the fuel injection points.

The circumferential component of the flow increases the path length for the mixing of fuel and air and promotes complete, efficient combustion. Also, the circumferential flow improves the fuel distribution and permits the use of fewer injection points, thereby reducing the number of fuel injectors normally required to one half. This reduction in the number of injectors provides a cost savings feature.

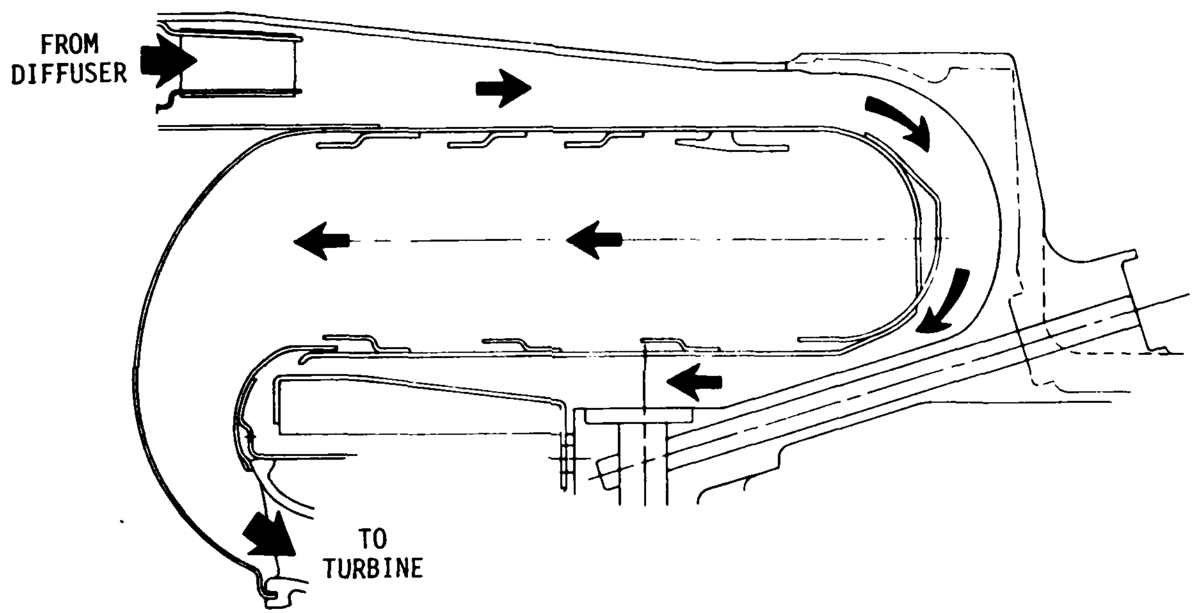


Figure 5. Combustor.

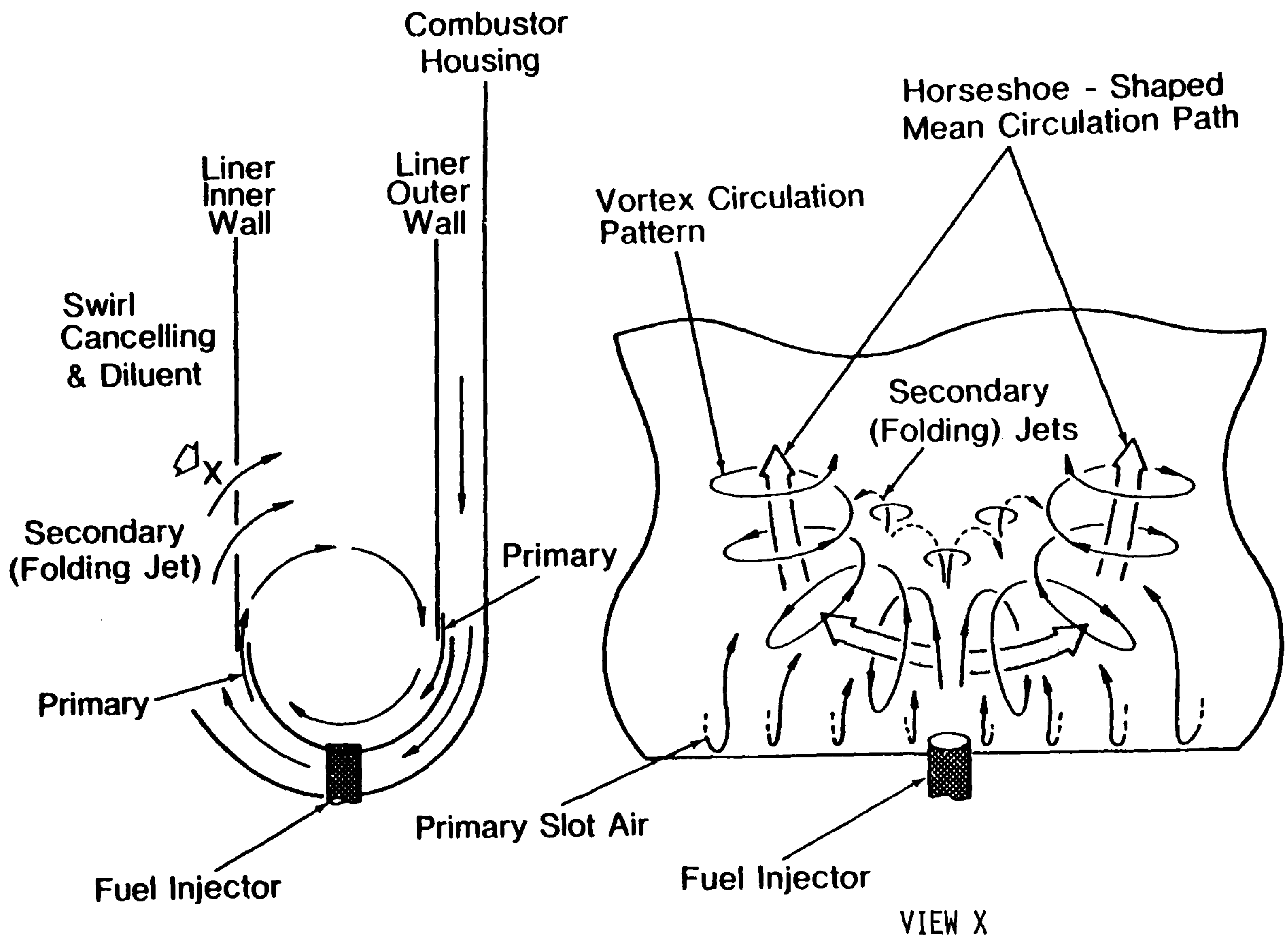


Figure 6. Circumferentially Stirred Combustor Flow Pattern.

Wall cooling design is based on the latest technology available from analytical and experimental studies. Factors influencing the cooling capability are cooling flow per unit of surface area, injection slot geometry, and the axial length to be cooled. The appropriate compromise among these factors has been used to optimize the cooling scheme. In this design, cooling is accomplished by means of external convection and a series of films introduced along the axial length of the wall.

The fuel manifold is of lightweight tubular construction. The tubing configuration is designed with flexibility so as to provide for thermal growth. The flow divider is an integral part of the manifold assembly to improve the contamination resistance of the system. Combustor housing drain valves are provided to purge the system of fuel after either a false start or engine shutdown.

The basic mechanical features of the combustor are the same for all of the existing LTS 101 engines. The LPU 101-700 combustor is unique in the inclusion of containment hardware.

The combustor housing, a sheet metal cone welded to the turbine support structure at the rear of the engine, is bolted to the air diffuser at the front end. The housing can be of uniform thickness for minimum cost, without being over stressed at any point along the cone. At the rear header, where variable thickness is required to have uniform stress, the wall is a casting that lends itself to variable wall thickness without additional cost. The bosses needed to mount the igniters and fuel nozzles are in the cast section of the combustor housing. For the LPU 101, additional material is cast into this area for power turbine containment.

The liner of sheet metal welded construction is secured to the combustor casing by four radial pins, which provide redundant support while allowing freedom for thermal expansion. The cylindrical shaped liner walls have splash cooling rings welded in place to provide for low manufacturing costs.

Containment of the gas producer turbine is accomplished by adding a separate metal ring located in the annular cavity between the liner inner wall and the turbine shroud structure. The addition of this material for containment has been done so that there is essentially no effect on combustor aerodynamic operation.

Engine Performance

Performance and detailed cycle characteristics of the LPU 101-700 Engine are presented below.

Cycle Selection

The selection of the cycle pressure ratio was based on component/cycle tradeoff studies to define the engine with the fewest number of compressor and turbine stages but consistent with competitive performance. A large cycle pressure ratio range was investigated at a turbine inlet temperature below 2000°F for engines having one centrifugal compressor with and without axial flow compressor supercharging. Efficiency levels were assumed to vary with stage pressure ratio for the axial and radial stages and are based on Avco Lycoming's test experience on state-of-the-art components.

Results in Figure 7 show where specific power and specific fuel consumption are plotted as a function of compressor overall pressure ratio for maximum power points. Separate investigations show that the selection of pressure rise based on maximum power also provide optimum specific fuel consumption values at part load. Three compressor configurations are shown: one centrifugal compressor plus two axial stages of 1.7 pressure ratio. Supercharged configurations are based on centrifugal compressor design pressure ratios of 4, 6, 8, and 10. It is seen that nonsupercharged configurations are low in specific power and high in specific fuel consumption when compared with the more efficient axially supercharged designs at the same cycle pressure ratio.

Relatively high specific power and low specific fuel consumption are obtained for the selected nominal cycle pressure ratio of 8.4 produced by a centrifugal design pressure ratio of 6 and supercharged by a 1.4 pressure ratio axial stage. No significant improvement in specific power is realized by adding a second supercharging stage to the configuration. The specific fuel consumption which improves by about 4 percent would not justify the added complexity of a second supercharger stage at the same cycle temperature.

This analysis led to the selected design cycle of Lycoming's first certified series of LTS 101 turboshaft engines. The LPU 101-700 engine essentially retains the same key cycle parameters of efficiency, overall pressure ratio, and cycle temperature ratio. Higher powers are reached by increasing the compressor channel height for increased airflow.

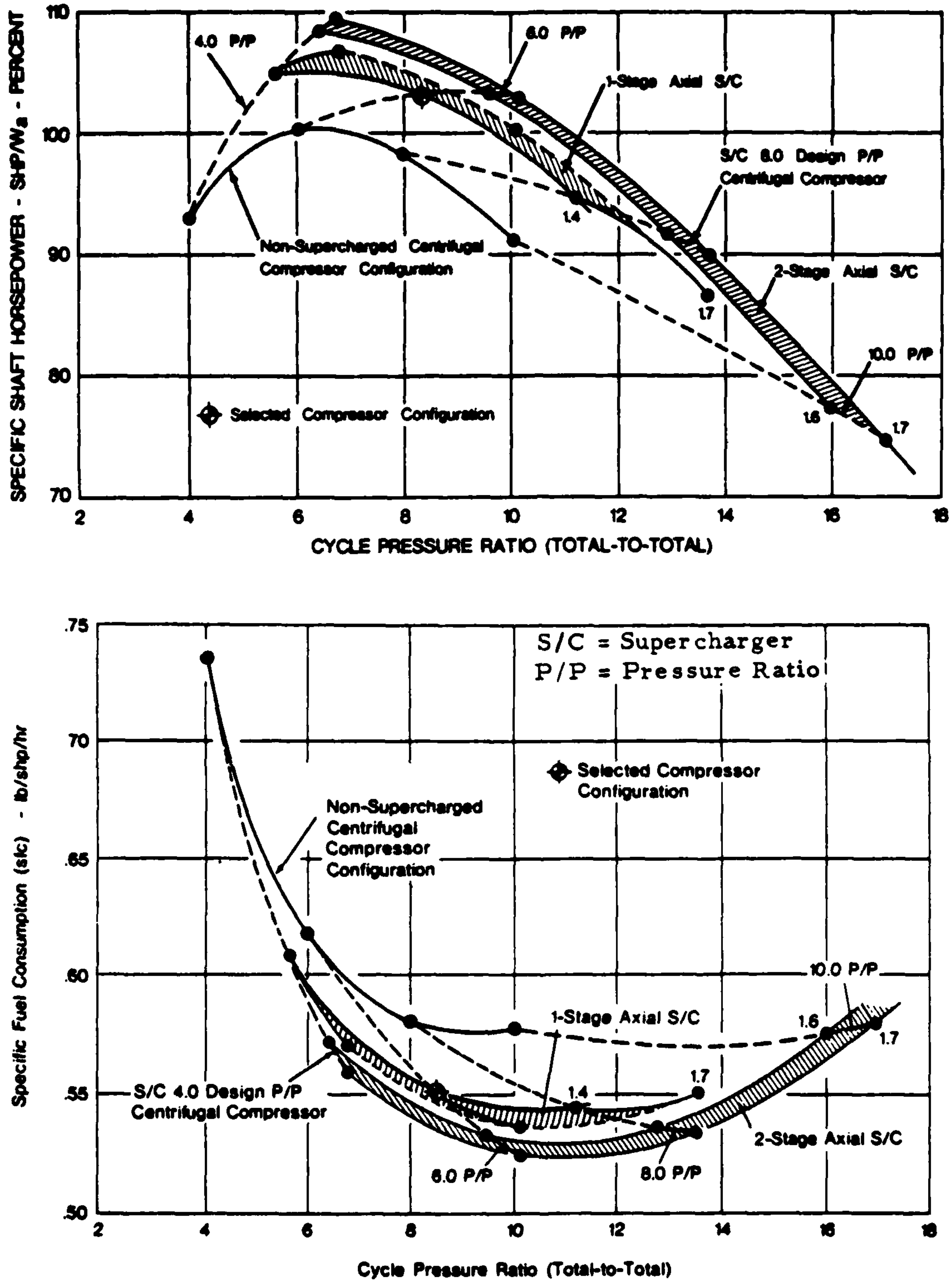


Figure 7. Five Lb/Sec Parametric Study - Specific Fuel Consumption Versus Cycle Pressure Ratio.

Overall Performance

The LPU 101-700 provides a maximum continuous shaft power of 456 horsepower at 37,000 rpm (Peak Rating), at standard sea level pressure; 130°F air at the engine inlet, with standard engine accessories; a standard exhaust diffuser of 95 square inch exit area; and no installation losses. At Peak Rating, 500 horsepower is available at sea level up to 109°F and up to a standard altitude of 8,500 feet. Table 1 lists the operational limits of the LPU 101-700. The engine operating envelope includes ambient temperatures from - 65° to + 130°F, with full ram recovery at Mach numbers from 0.0 to 0.5 at altitudes from sea level to 25,000 feet. The available maximum continuous power at sea level, as a function of inlet temperature and at standard atmosphere altitude, is shown in Figures 8 and 9, respectively.

Transient Characteristics

The LPU 101-700 engine attains surge-free transient power operation through the use of an inlet air modulator ring located in front of the axial rotor. This ring is positioned as a function of compressor pressure ratio, and it modulates from its fully immersed to fully retracted position between approximately 85 and 92 percent referred compressor speed. This device provides surge-free operation during speed transients to full power.

Cooling and Heat Transfer

Cooling Air Network

Cooling air is supplied to the turbine components through a network of passages as shown in Figure 10. The network is designed to be simple and insensitive to off-design operating conditions. All of the cooling air, except for the seal leakage at the compressor impeller rear face, is compressor diffuser discharge air taken from this combustor area, including air assumed for overboard leakage through the flange and oil sump. The cooling air for the first stator vanes, inner shroud, and first gas producer disc is directed along the combustor curl to provide curl cooling along the way.

TABLE 1. OPERATIONAL LIMITS

Engine Ratings	Output Torque (ft-lb)	Output Shaft Speed (rpm)	Maximum Gas Generator (Speed) (rpm)	Maximum Measured Temp. (°F) Station 4.5
Starting	-	-	-	1650*
Transient	75	38,850	49,300	1450
Maximum Continuous	71	37,000	48,346	1400
No Load	0	37,000	N. A.	N. A.

* Time Limit: 12 Seconds Above 1530°F

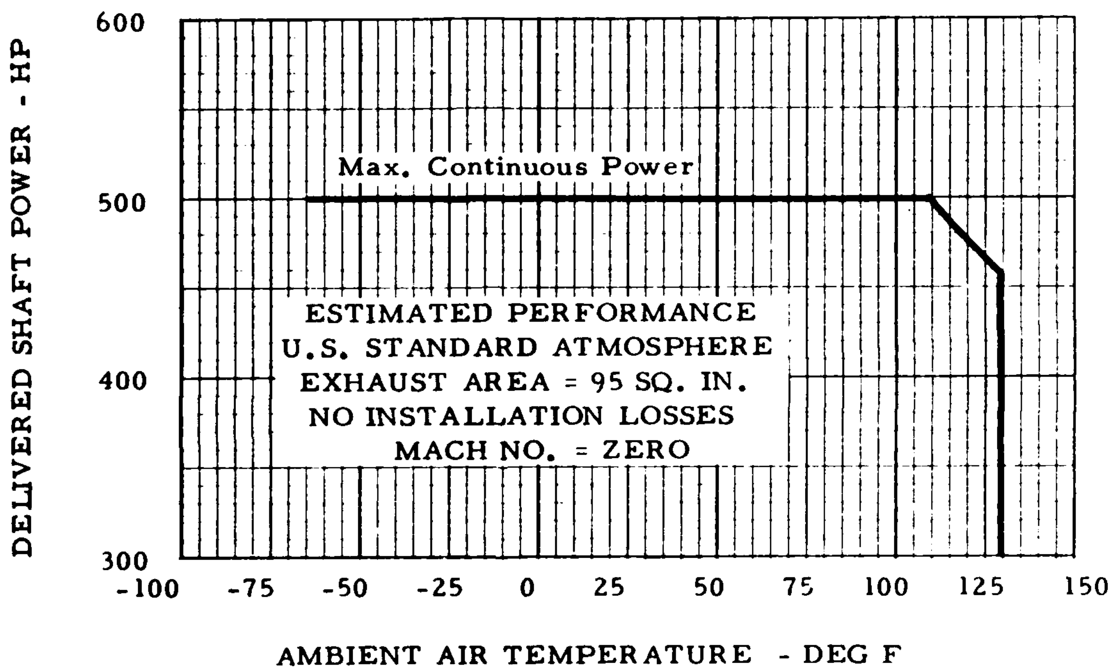


Figure 8. Estimated Temperature Lapse Rate.

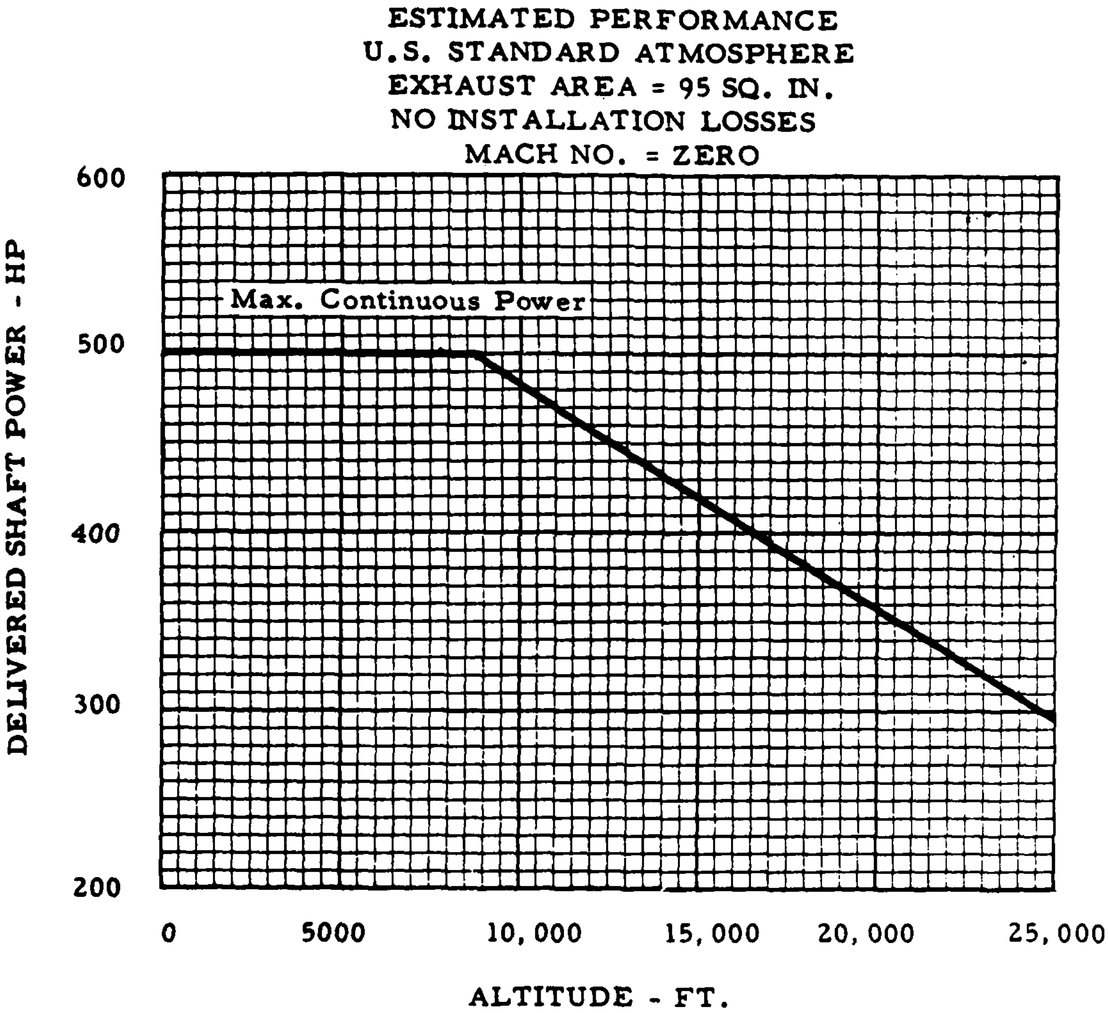


Figure 9. Estimated Altitude Performance.

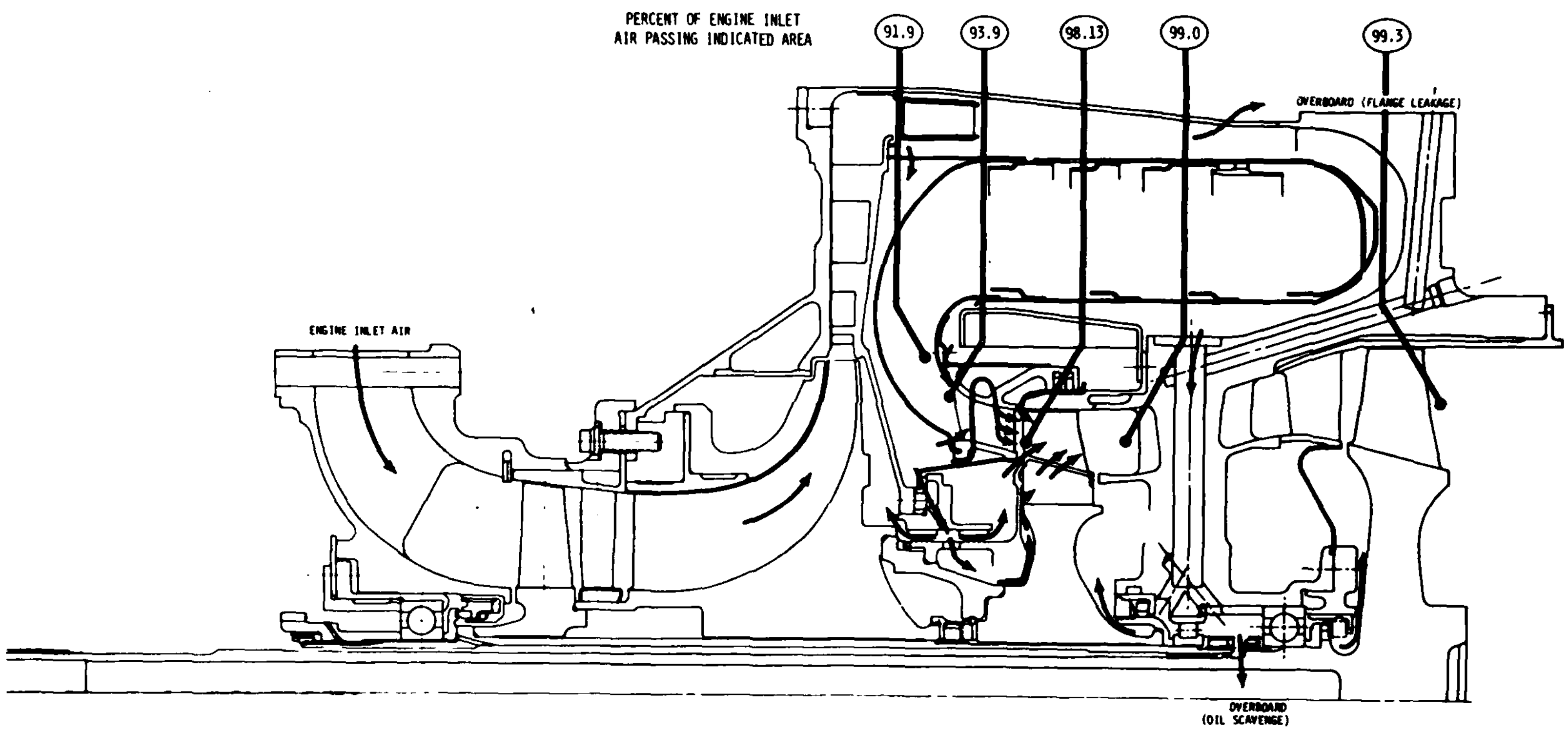


Figure 10. Cooling Air Network.

Part of this air is used for first nozzle vane-cooling and for film cooling the nozzle inner shroud. The remaining airflow passes through preswirl holes inclined 45 degrees in a plane perpendicular to the engine axis. A portion of this air then flows through the downstream labyrinth seal to pressurize the cavity between the nozzle inner support and seal plate, thereby keeping hot gasses out of the cavity. Another portion of the air flows between the labyrinth seals through 12 large rectangular slots in the spacer and then flows between the seal plate and gas producer disc for blade shank and disc cooling. Coolant air flows up the disc face, through the disc blade-root-serrations, and, subsequently, into the gas stream. Additional air leaks through the upstream labyrinth seal between the impeller aft face and diffuser flange. As mentioned above, preswirling the air results in cooler air temperatures ($\approx 100^{o}F$) and eliminates work by the turbine pump to bring the cooling air up to speed. Air is also used to film-cool the nozzle's outer shroud. This film-cooling air lowers the shroud metal temperatures and provides more favorable temperature gradients in the nozzle assembly. A small amount of cooling air is also used to cool the aft face of the first rotor disc. Additional air leakage exists over the gas producer rotor shroud, thus providing film cooling and favorable rotor tip clearances.

Cooling air is directed through the interturbine struts to pressurize and cool the oil seals of the turbine bearing package. These airflows also cool the rear face of the first turbine disc and the front face of the second turbine disc.

Engine Skin Temperature and Heat Rejection

Engine skin temperatures at design (worst engine, $130^{o}F$, sea level day), as a function of heat rejection rate, are shown in Figure 11 for various zones of the engine. The surface emissivity of the engine is shown in Figure 12. These data establish the engine installed cooling requirements.

Typical skin temperatures for zero heat rejection are:

Gearbox	$290^{o}F$
Combustor	$680^{o}F$
Turbine Duct	$1166^{o}F$

Containment Temperatures

Containment material temperatures at design (worst engine, $130^{o}F$, S. L. day) are shown on Figure 13 for the engine areas requiring containment. With the exception of the gas producer rotor containment, these temperatures follow directly from the engine skin temperatures (Figure 11).

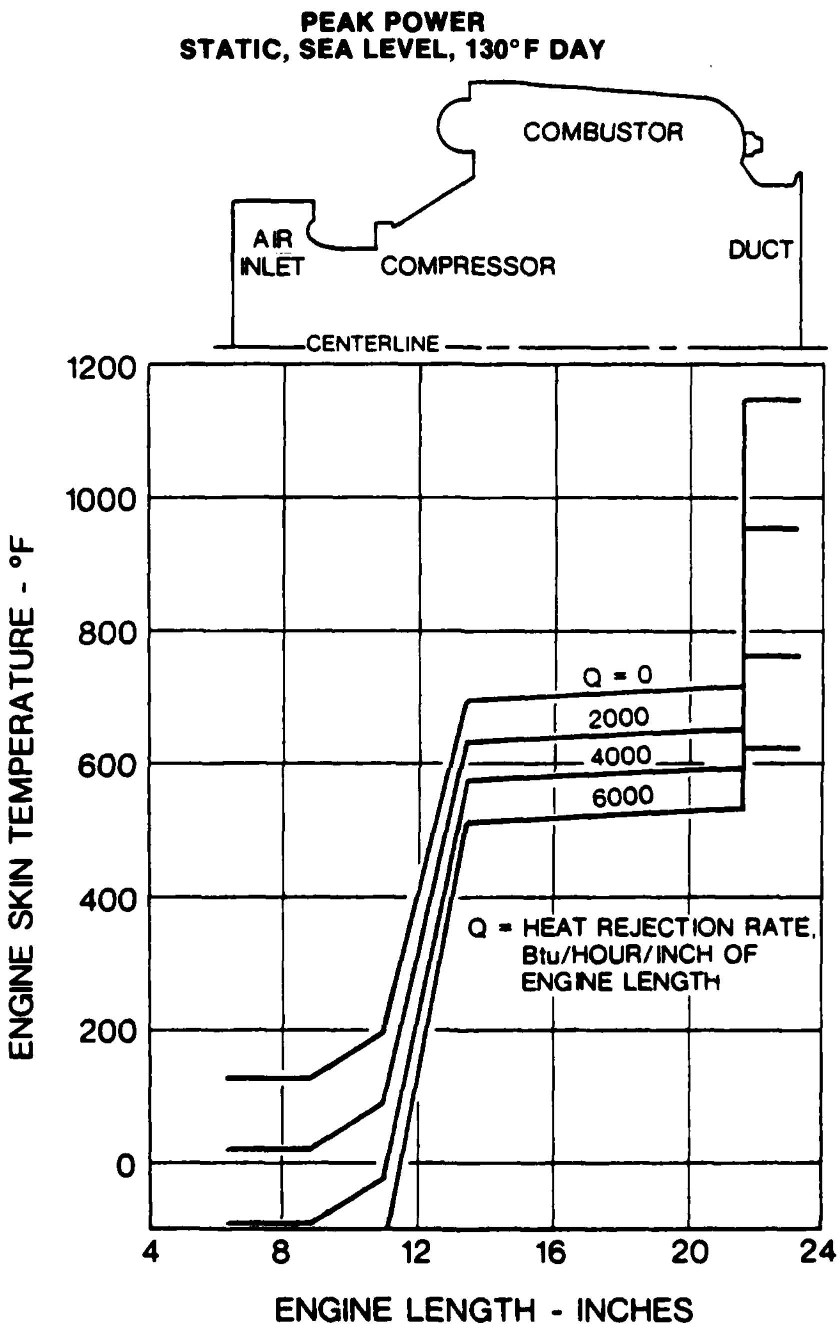


Figure 11. Estimated Engine Skin Temperature for Design.

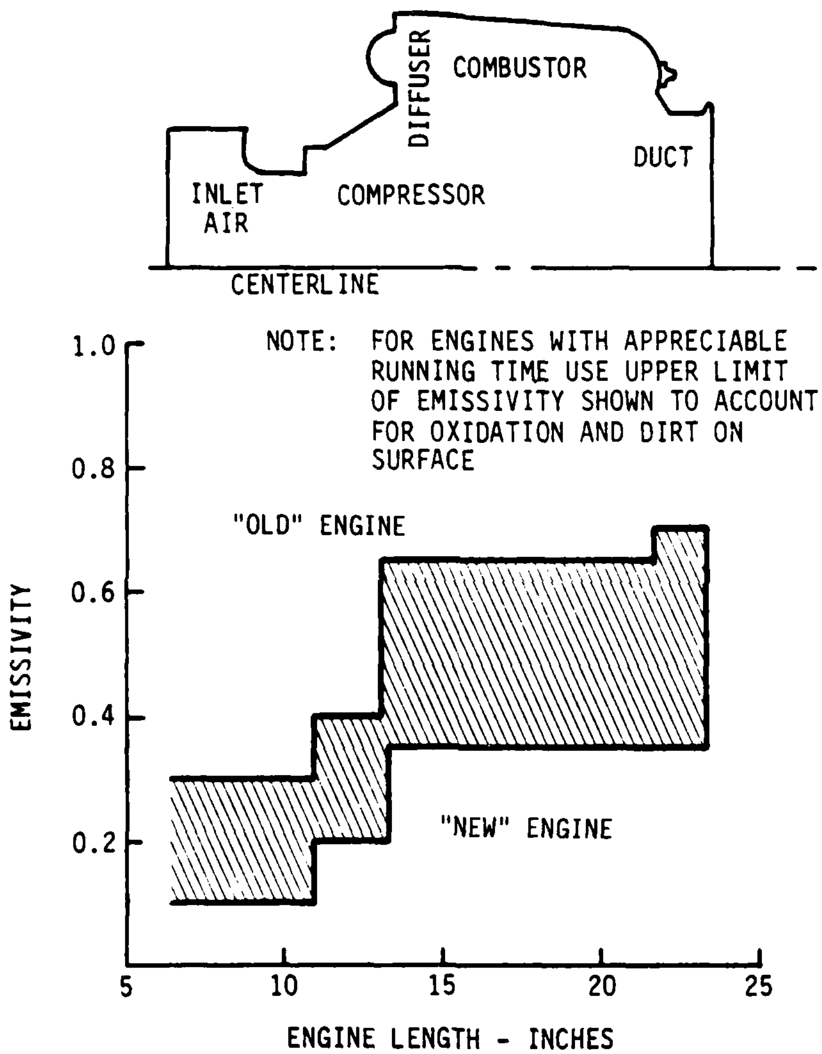


Figure 12. Surface Emissivity.

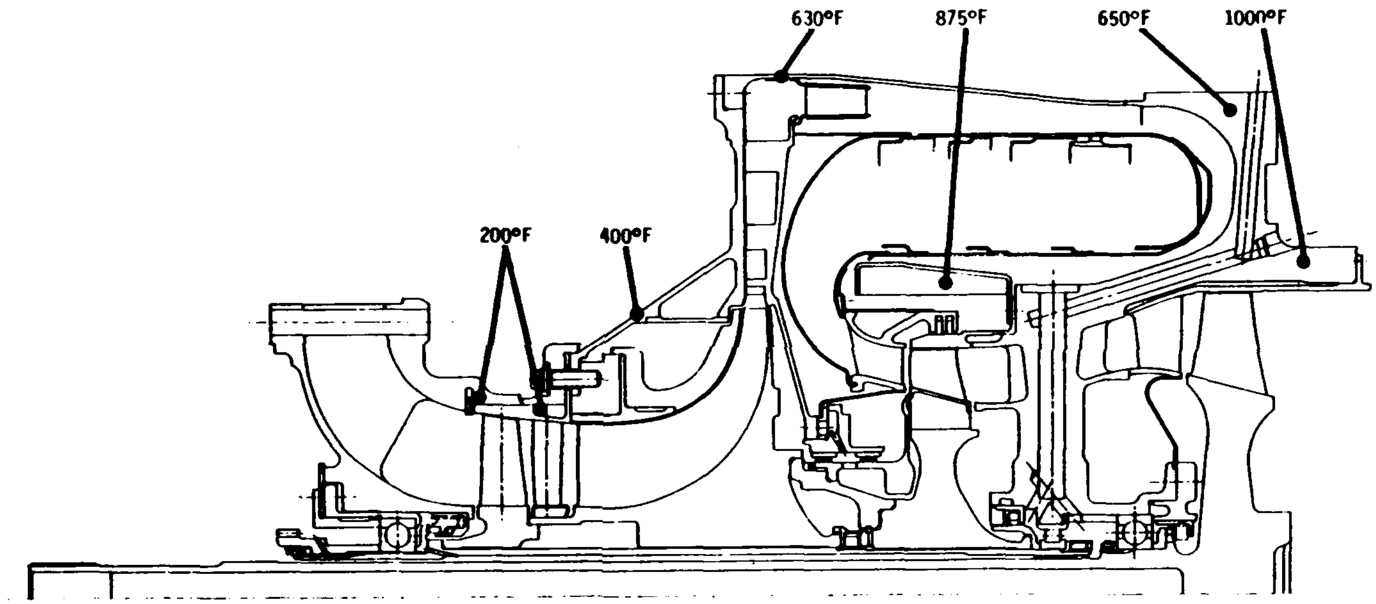


Figure 13. Temperatures of Containment Materials at Peak Power.

Rotor containment temperatures were calculated as follows:

1) Extrapolating by metal effectiveness the area weighted temperatures of the surrounding metals (i.e., combustor, nozzle outer shroud, and curl, etc.) previously determined from thermopaint and T/C measurements to the HPAPU design conditions. This "weighted" temperature was assumed equal to the containment temperature.

2) Considering an energy balance for the containment of all possible sources of heat (i.e., radiation, free and forced convection, etc.) absorbed or rejected by the containment to the surrounding metals and airflow.

In general, good agreement was obtained by using both of the above methods. As a conservative approach, however, the method yielding the highest temperature was used.

Method of Containment

Containment Analysis

The possibility of sudden failure of high-speed rotating hardware requires an assessment of the damage incurred in case of such a failure, by the containment structure and the likelihood of hazards to the surrounding area. Containment analyses performed at Lycoming use a computerized analysis method that was specifically developed to evaluate the major structural material and operating parameters affecting fragment/ring behavior following the burst of a rotating element. To date, Lycoming's engine experience with this method indicates that it is somewhat conservative. That is, predicted containment always contained, predicted noncontainment occasionally contained. This experience is directly relatable to the design and analysis of flywheel containment structures.

The containment ring design/analysis method uses an energy-balance criterion which relates the kinetic energy of the rotor fragment to the strain energy absorption capability of the surrounding containment structure. Penetration of the innermost ring occurs whenever the energy of the attacking fragment, taken with respect to that absorbed by the ring material being plastically worked, equals or exceeds the appropriate criterion value. The remaining attack energy is then imposed on each subsequent ring in sequence, until the projectile energy is totally absorbed, or the fragment exits the outermost ring. In the latter case, neighboring areas then become vulnerable to the residual energy still possessed by the moving fragment.

A disc fragment exiting from a turbine stage is illustrated in Figure 14. Here, the initial kinetic energy of the fragment and its translational and rotational components are computed based on its shape, material, and fracture conditions. Determination of the actively deformed volume of plastically strained material is based on the thickness of the impacted ring, the impact area under the fragment contact surface, and the distance traversed by the plastic stress waves emanating from the impact region during the impact interval. The specific strain energy absorption capacity of the ring material is defined by its stress/strain curve.

Excellent correlation of the analysis results with the disc burst experiments performed at the Naval Air Propulsion Test Center* have been obtained. Figures 15 and 16 show the experimentally determined energy criterion lines (hereafter referred to as correlation curve), which in all cases studied accurately separated penetration from contained tests. Note that a correlation analysis was made for total fragment kinetic energy (Figure 15), as well as for translational kinetic energy (Figure 16). Both approaches are currently used in industry. Figure 15 is more universal in that it covers multisection fragments, whereas Figure 16 holds only for three fragment bursts.

Either of the previous figures is applicable in the appraisal of the containment design for the LPU 101-700, since the design requirement is to satisfy containment for a tri-hub burst. An ample margin of safety of the same approximate value is necessary in each case to assure containment adequacy.

Containment Design for LPU 101-700

Figure 17 shows the changes that were made in the basic engine to satisfy the containment requirements at gas producer and power turbine rotor speeds that are 5 percent above the maximum trip speed for each rotor. (See Table 2 for the definition of these speeds).

Details of each containment package are provided as follows: Figures 18 and 19 define the axial and centrifugal compressor shrouding; Figures 20 and 21 show the additional ring that was incorporated over the gas generator turbine; and Figures 22 and 23 cover the circumferential shrouding and axial containment treatment, respectively, for the power turbine. Experience with the basic LTS 101 engine (as well as with the T55-L-11) has proven an exhaust nozzle and centerbody that are effective in restricting aft displacement of the power turbine rotor in the event of shaft failure. It also is effective in the control of axially ricocheting debris from shed blades. Consequently, it is a major benefit in the overall containment design assessment.

*Mangano, G.J., et al "Rotor Burst Protection Program", Naval Air Propulsion Test Center, Report NAPTC-PE-98, March 1977.

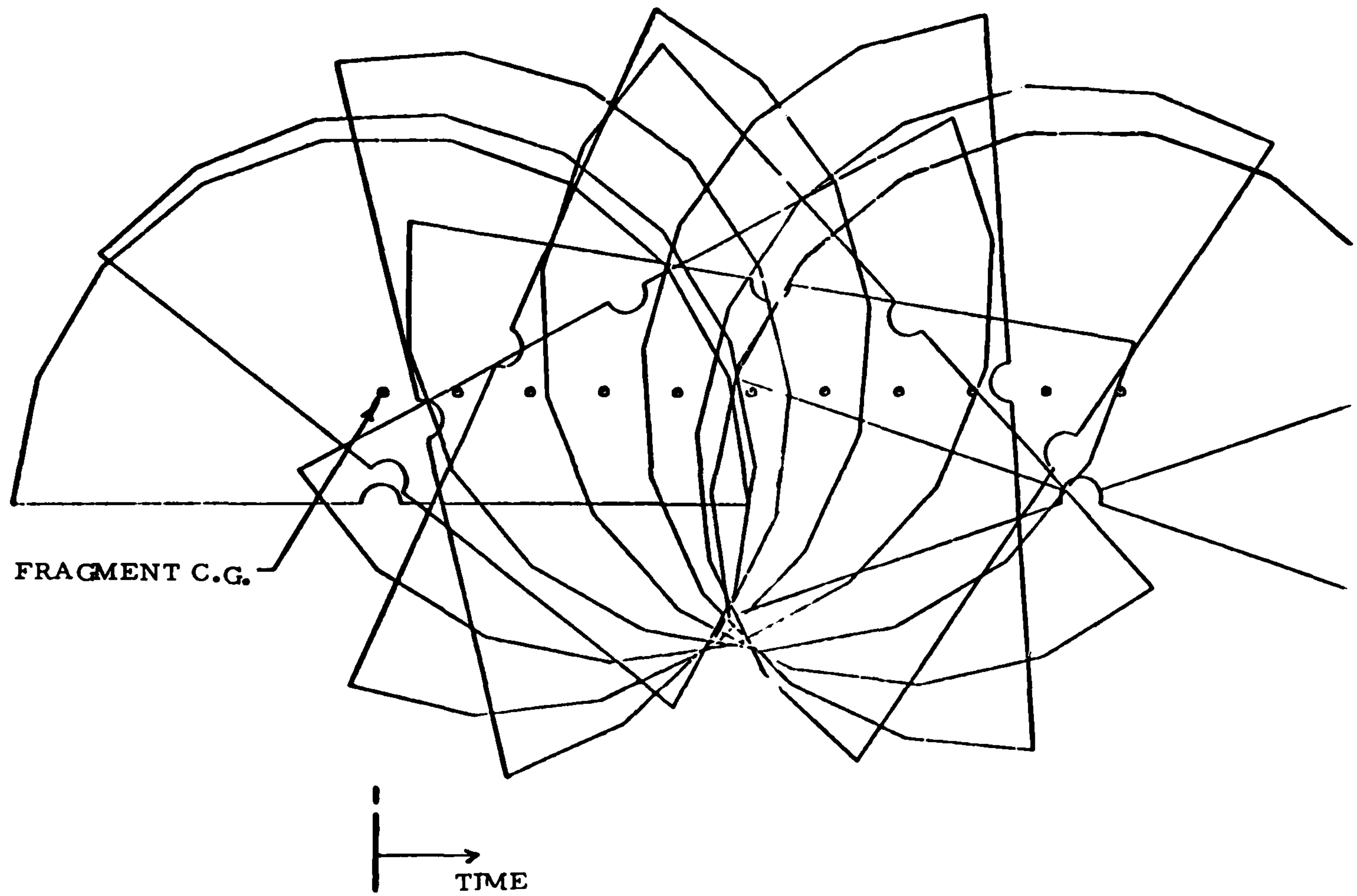


Figure 14. Trajectory of One-Half Segment Disc.

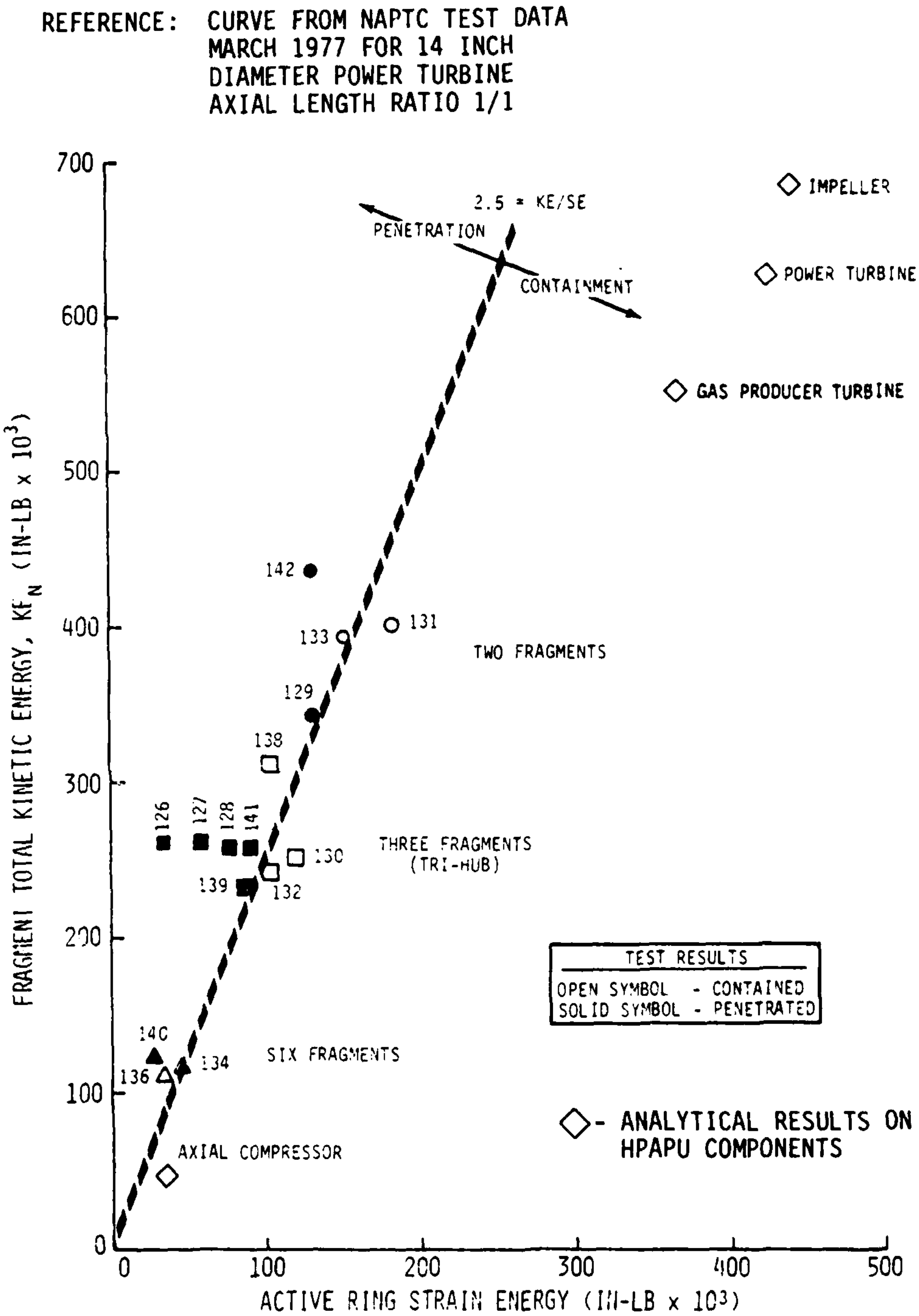


Figure 15. Fragment Total Kinetic Energy Versus Active Ring Strain Energy.

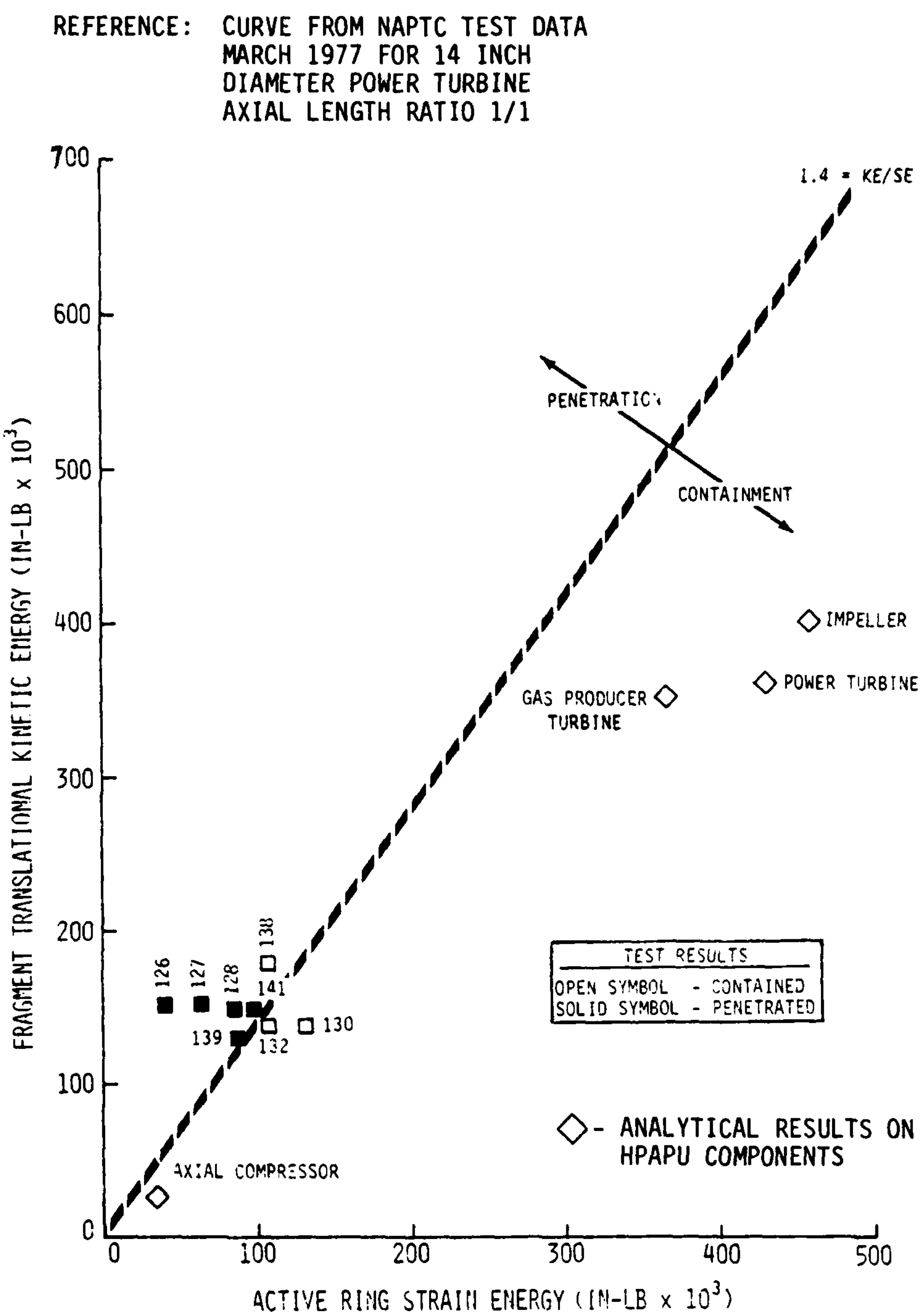


Figure 16. Fragment Translational Kinetic Energy Versus Active Ring Strain Energy.

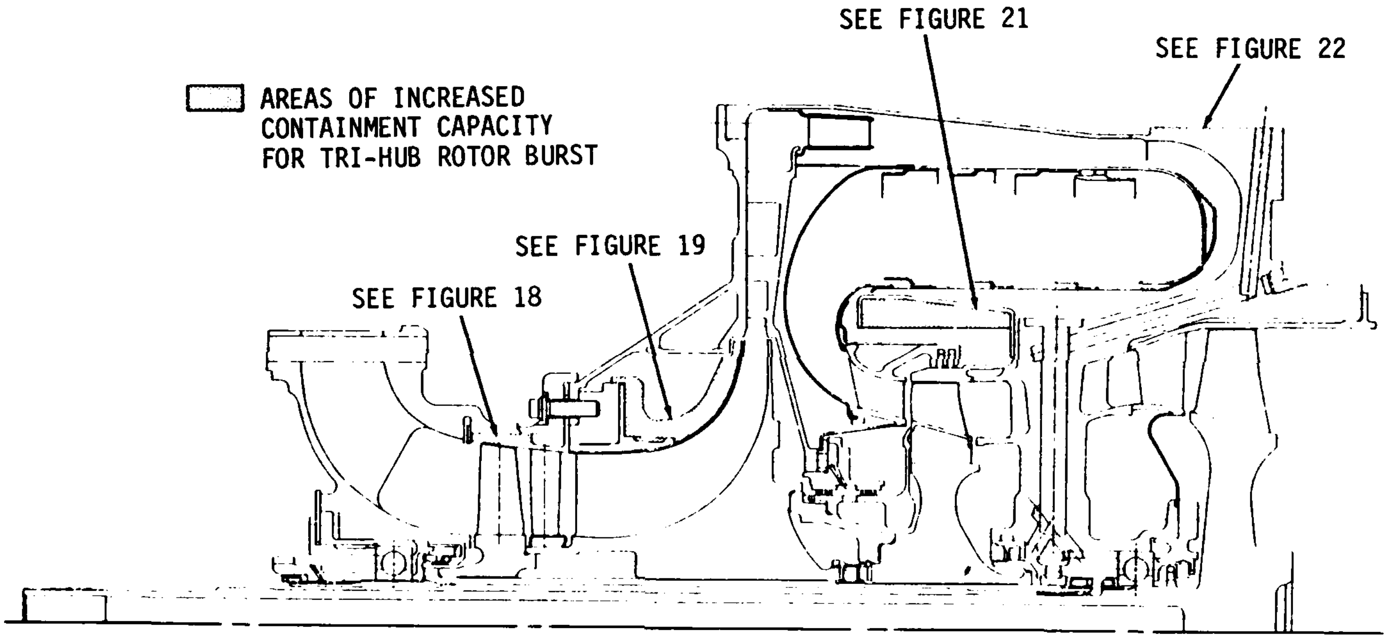


Figure 17. Containment Design.

TABLE 2. CONTAINMENT SUMMARY - TRI-HUB BURST

Item	Axial Compressor	Centrifugal Compressor	Gas Producer Turbine	Power Turbine
Containment Speed (rpm)	51,770(1)	51,770(1)	51,770(1)	41,570(2)
Weight of Each Fragment (lb)	0.5	4.8	2.9	3.7
Translational Kinetic Energy of Each Fragment (in-lb)/Safety Factor*	30,000/1.55	387,000/1.68	333,000/1.55	365,000/1.64
Total Kinetic Energy of Each Fragment (in-lb)/Safety Factor*	49,500/1.68	686,000/1.63	559,000/1.65	626,000/1.72
Weight of Material Added for Containment (lb)	0.3 (Hastelloy X)	7.1 (Hastelloy X)	7.4 (Hastelloy X)	17.5 (Stellite 31)

(1) Gas Producer Rotor Speed Limit (100% N_I = 47,867 rpm)

Worst Engine Rating Speed	=	101.00%
Overspeed Trip Margin	=	2.00%
Maximum Trip Speed	=	103.00%
Tri-Hub Containment Speed (1.05 x 103%)	=	108.15%

(2) Power Turbine Speed Limit (100% N_{II} = 37,000 rpm)

Rated Speed	=	100.00%
Maximum Transient Overshoot Margin	=	5.00%
Overspeed Trip Margin	=	2.00%
Maximum Trip Speed	=	107.00%
Tri-Hub Containment (1.05 x 107%)	=	112.35%

*Relative to NAPTC Correlation curves

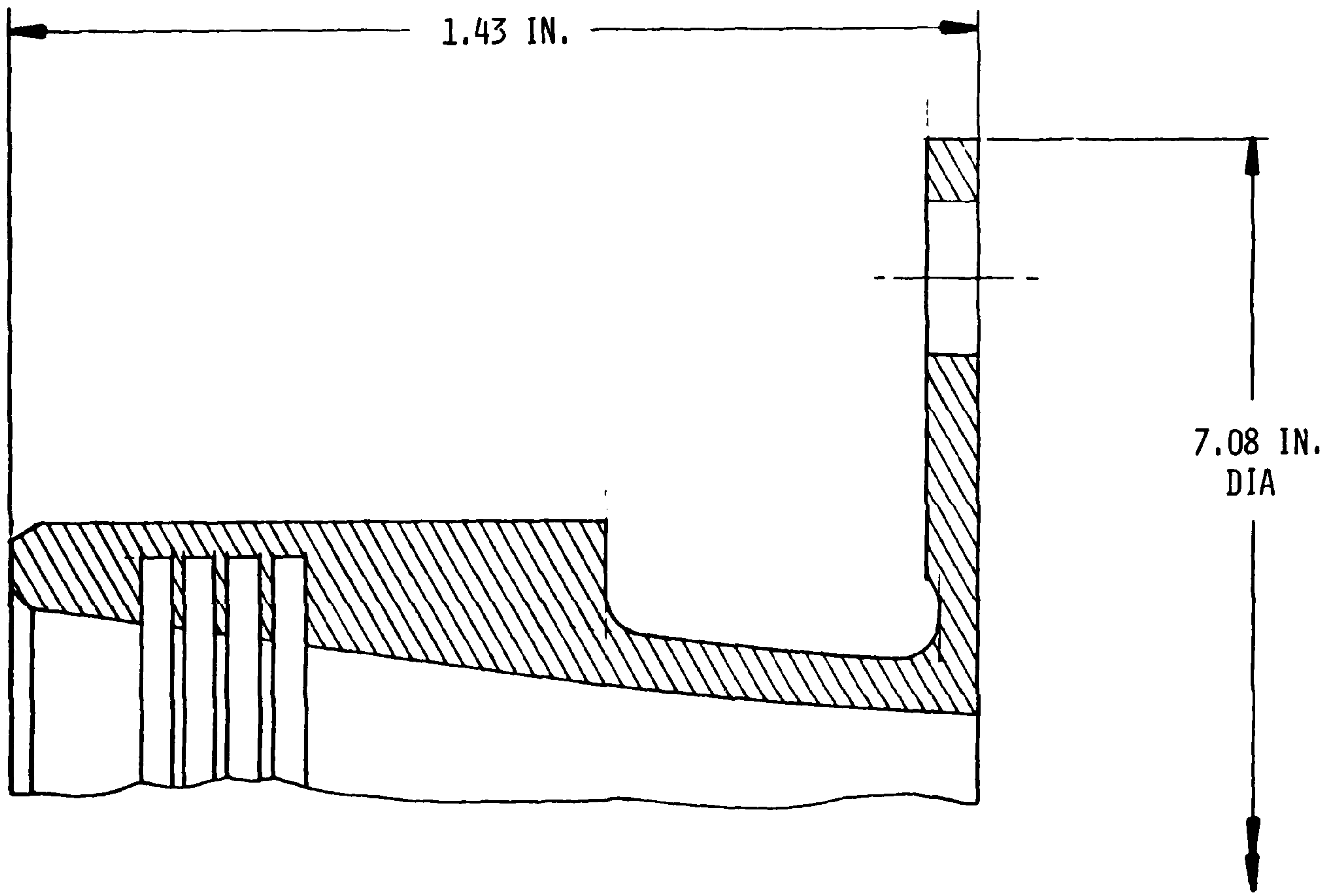


Figure 18. Axial Compressor Shroud.

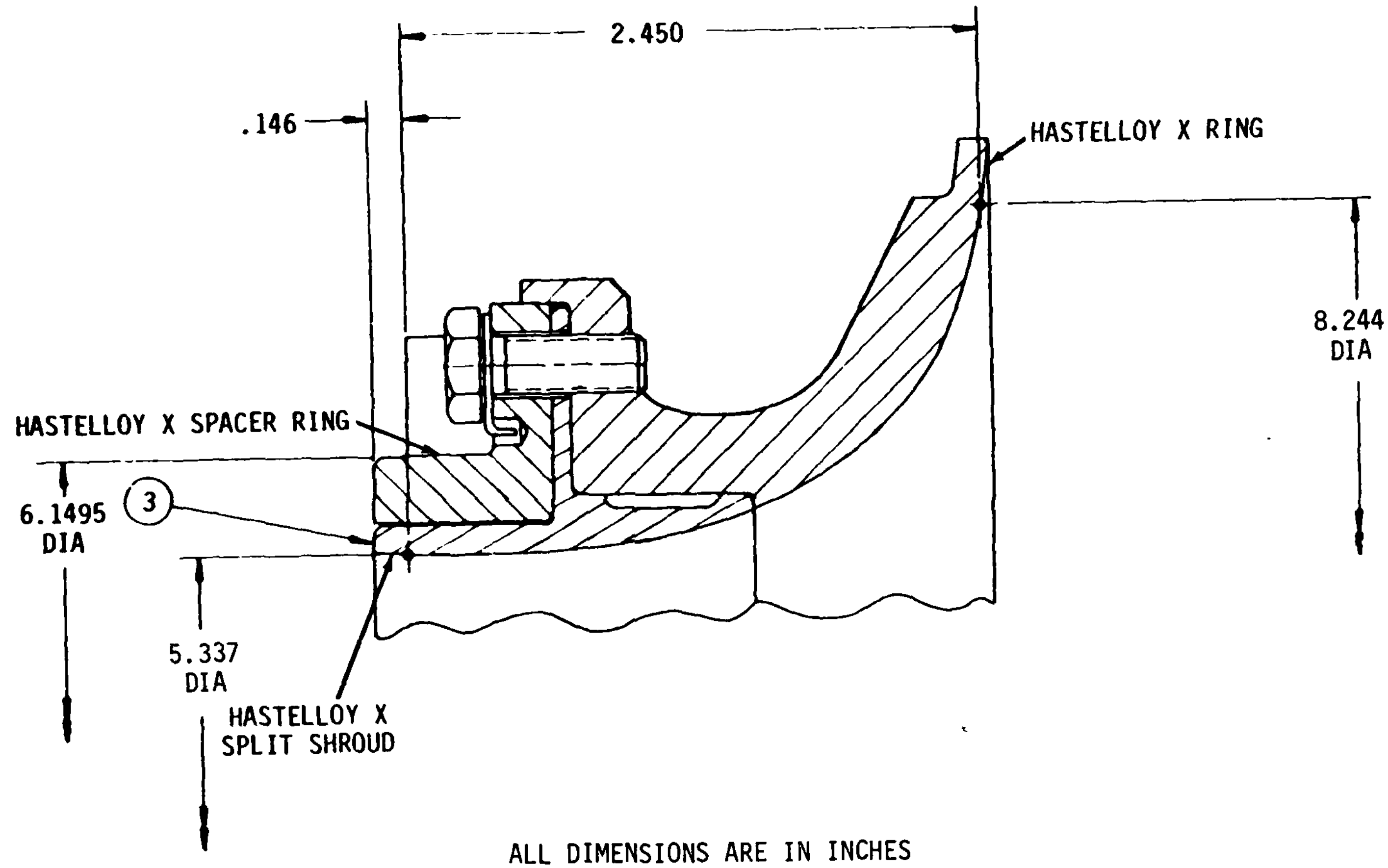


Figure 19. Centrifugal Impeller Shroud Assembly.

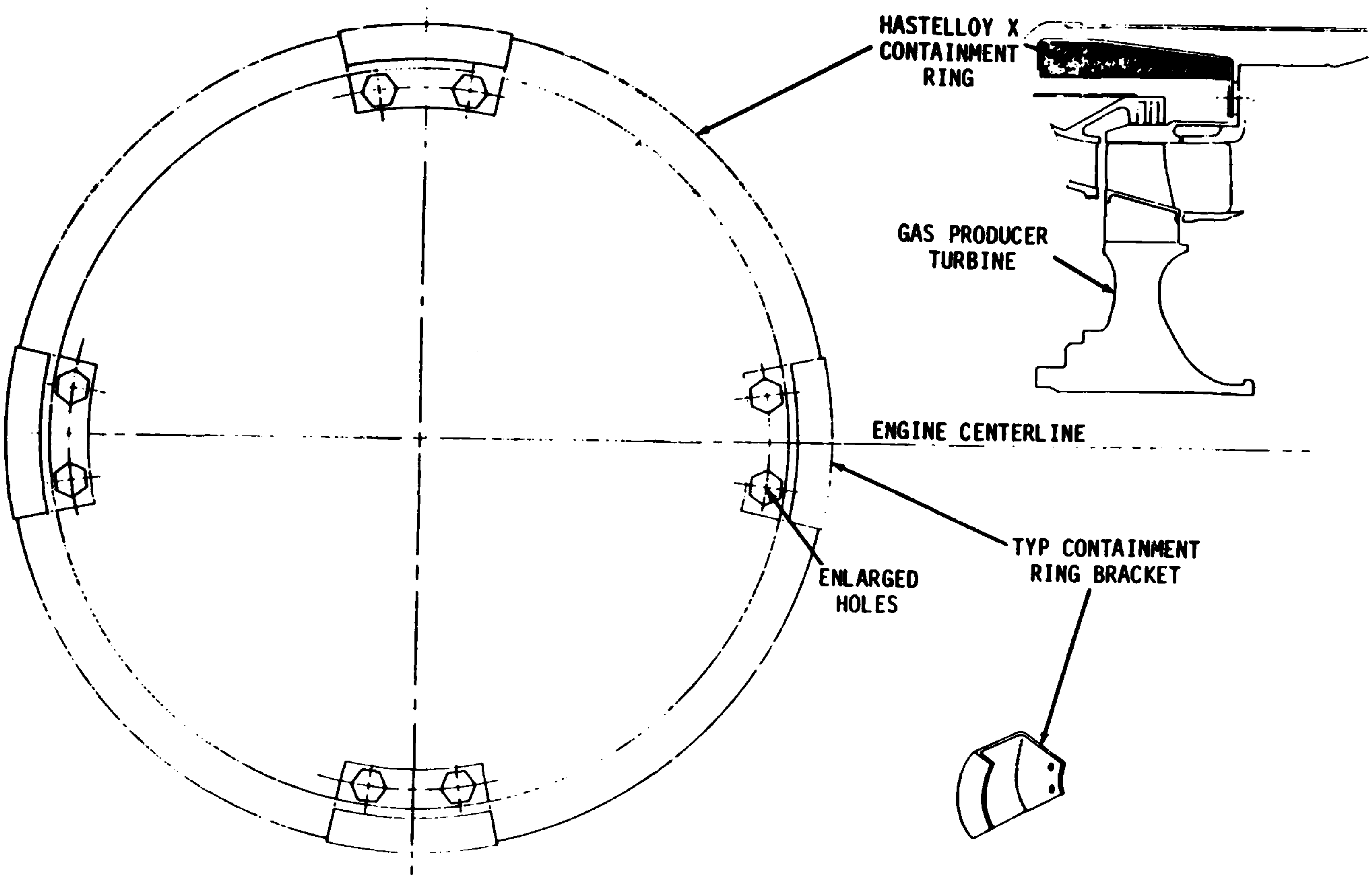
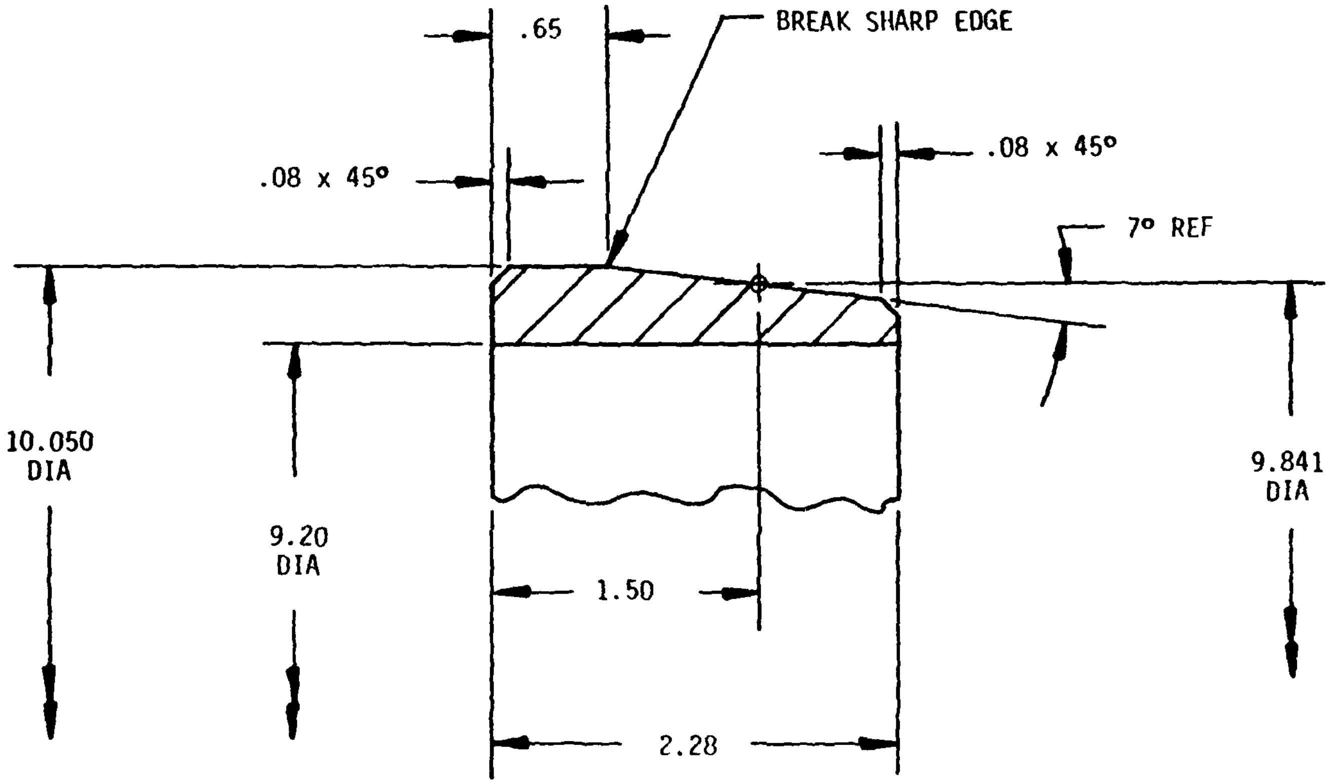


Figure 20. Gas Producer Containment Ring Assembly.



ALL DIMENSIONS ARE IN INCHES

Figure 21. Gas Producer Turbine Containment Ring.

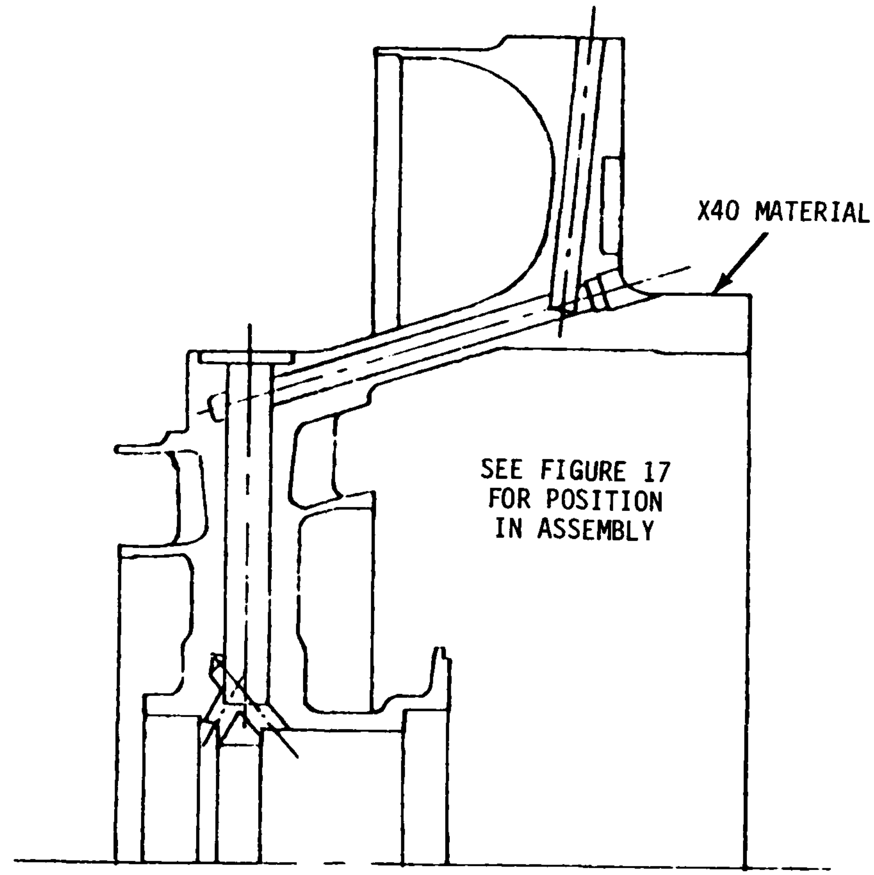
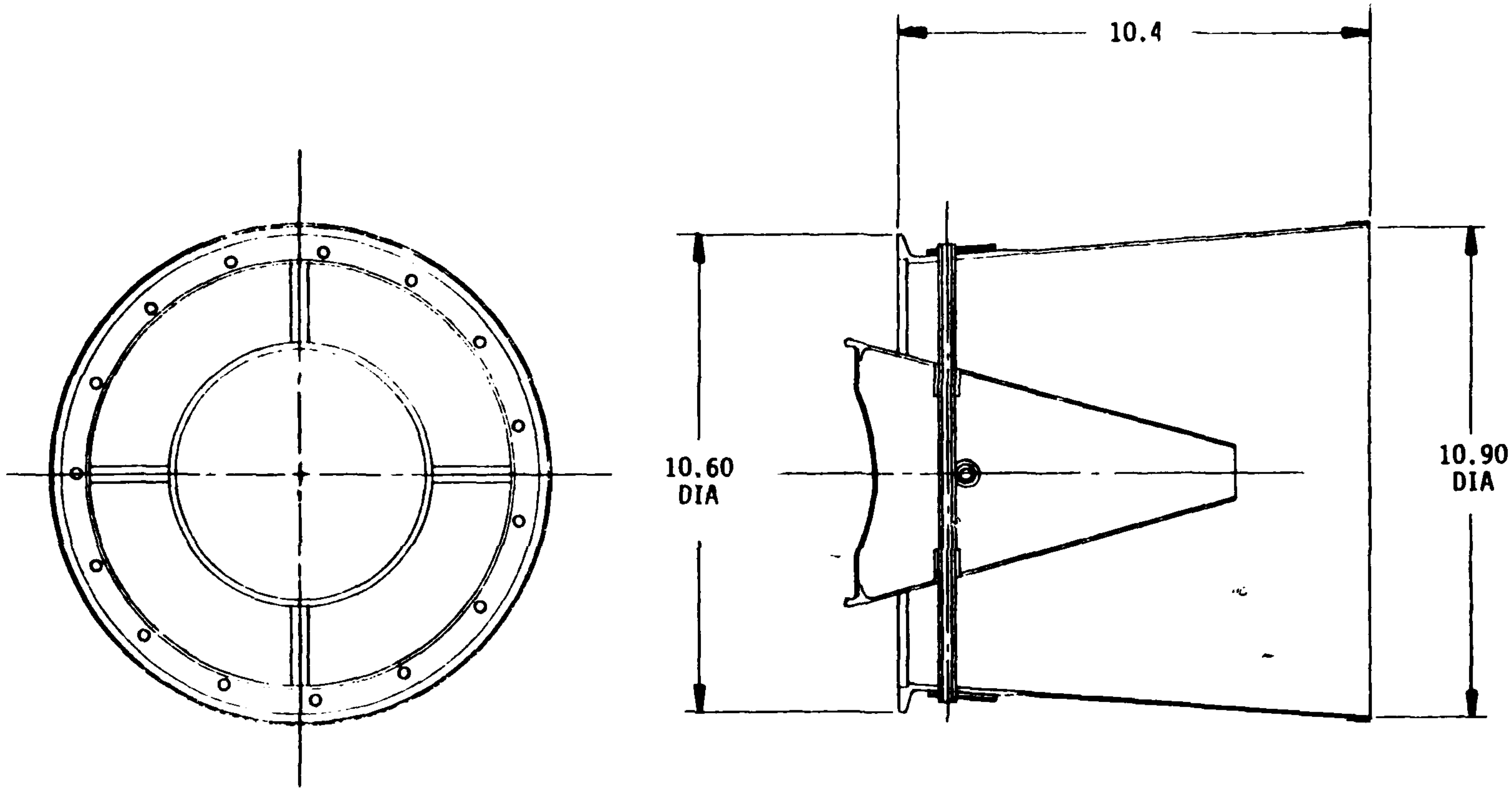


Figure 22. Power Turbine Containment - Combustor and Rear Bearing Support Housing.



ALL DIMENSIONS ARE IN INCHES

Figure 23. Exhaust Nozzle Assembly.

Results of the analysis of the entire containment design are given in Table 2 for a gas producer speed of 51,770 rpm (108.15% N_1) and a power turbine speed of 41,570 rpm (112.35% N_2), assuming a tri-hub burst for each rotor. Applicable material properties at the operating temperature of the environment were used to provide the specified margins of safety relative to the correlation curves and added weight. Safety margins of approximately 1.6 are common to both energy bases (that is, total kinetic and translation energy). These are defined as the ratio of the active ring strain energy capacity for each rotor, to the required value of strain energy nec- essary to effect containment (for the particular value of kinetic energy) shown by the dashed correlation curves in Figure 15 and 16.

Location of containment characteristics for each rotor relative to the correlation curves are noted in Figures 15 and 16 to be ample for structural safety.

2.3 HPAPU DEMONSTRATOR SYSTEM

General

The HPAPU Technology Demonstrator System consists of an Avco Lycoming power producer, driving, via an adapter gearbox, a Sundstrand accessory gearbox with installed accessories. The Sundstrand accessory gearbox and driven accessories were existing developed designs at the start of the program. These items were selected to emphasize that development was to be restricted to the power producer and its fuel control. The Sundstrand accessories include:

1. A load compressor which provides pneumatic capability

2. A generator for electrical power

3. An air-oil heat exchanger for lubrication system cooling

4. A cooling fan which is integral to the accessory gearbox

5. An oil reservoir

6. An electric start motor

7. An electronic controller which provides fully automated APU operation

8. A fuel control system.

Figure 24 is a schematic diagram of the HPAPU Demonstrator system. Figures 25 through 28 show the HPAPU configuration and component arrangement.

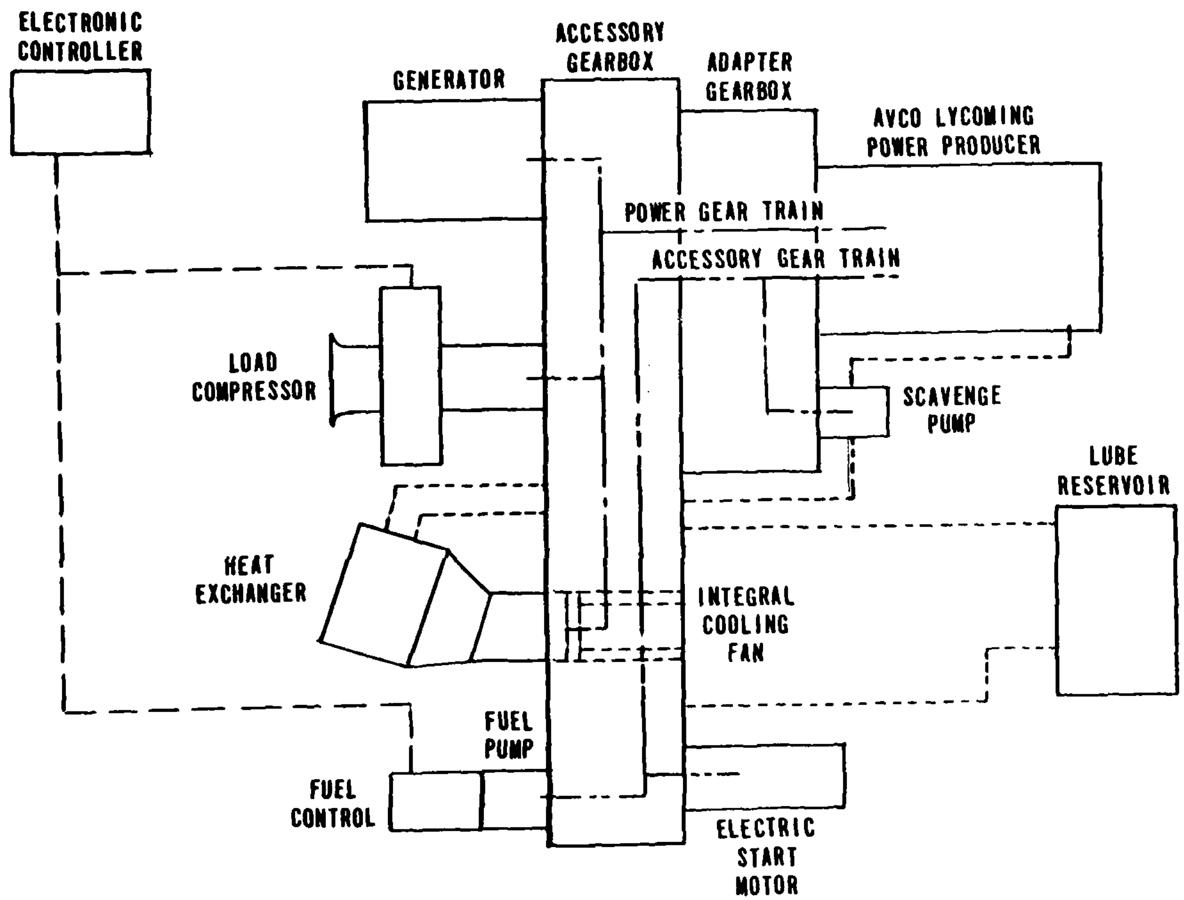


Figure 24. Schematic Diagram of the HPAPU Demonstrator System.

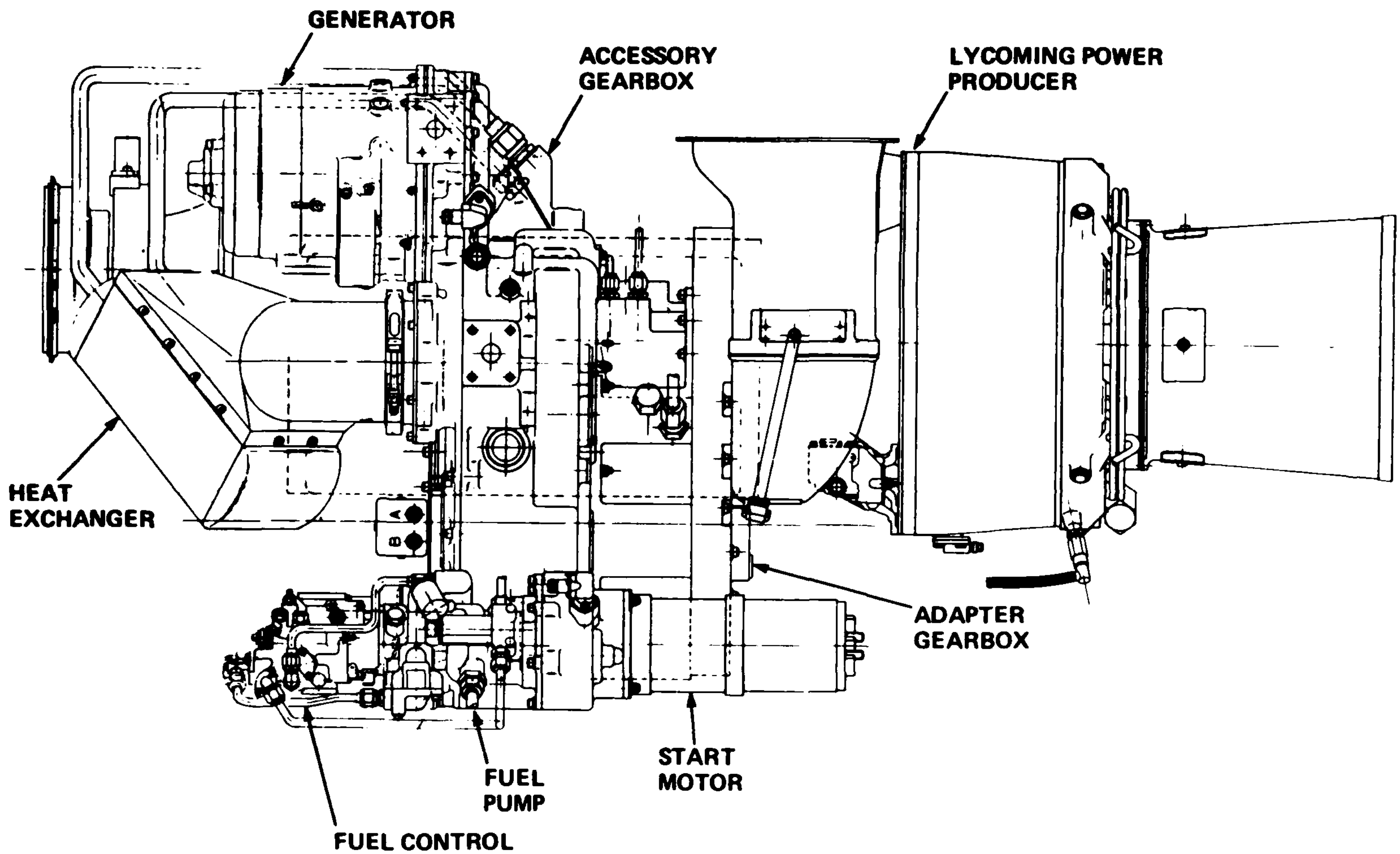


Figure 25. HPAPU - Left Side View.

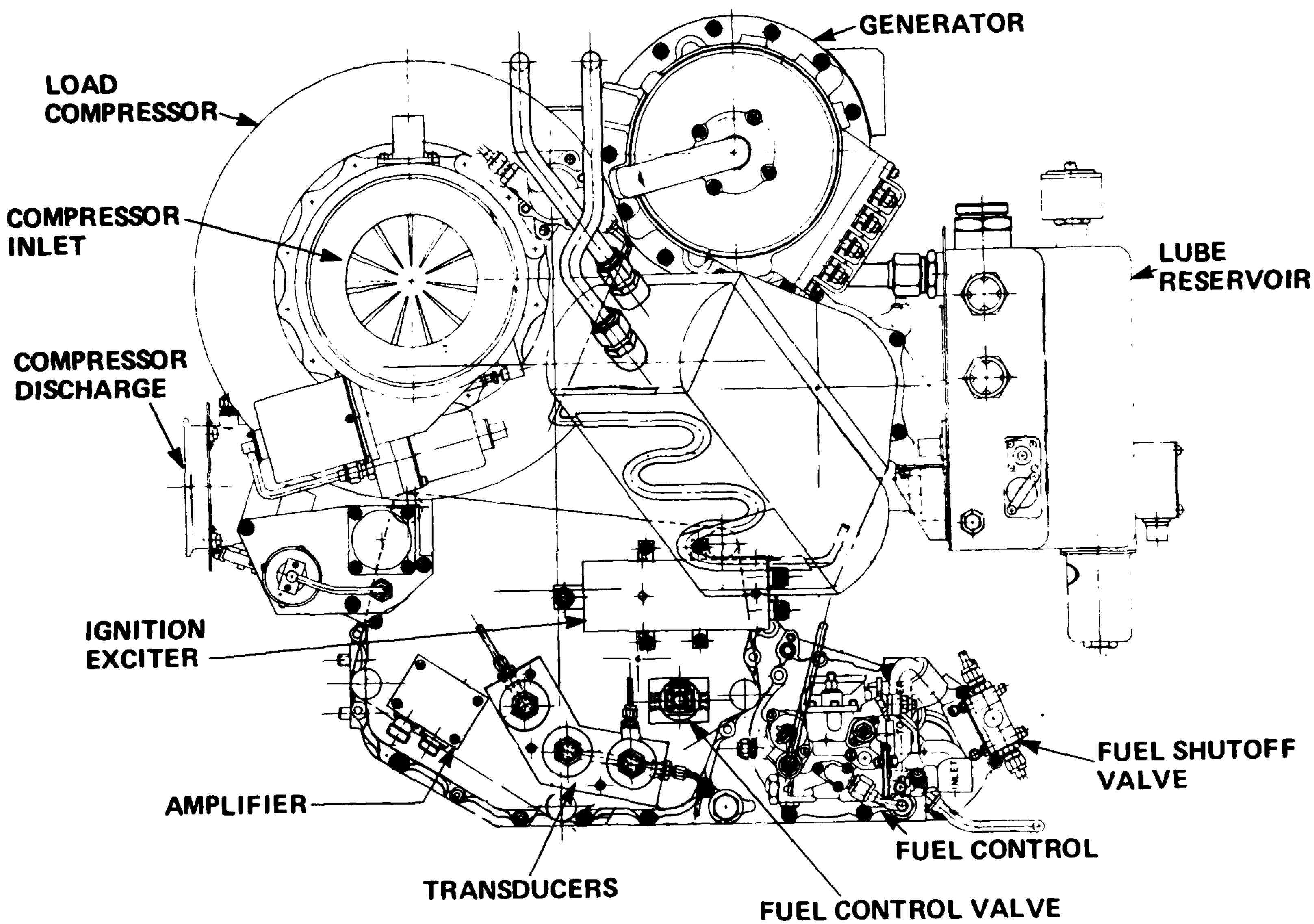


Figure 26. HPAPU - Front View.

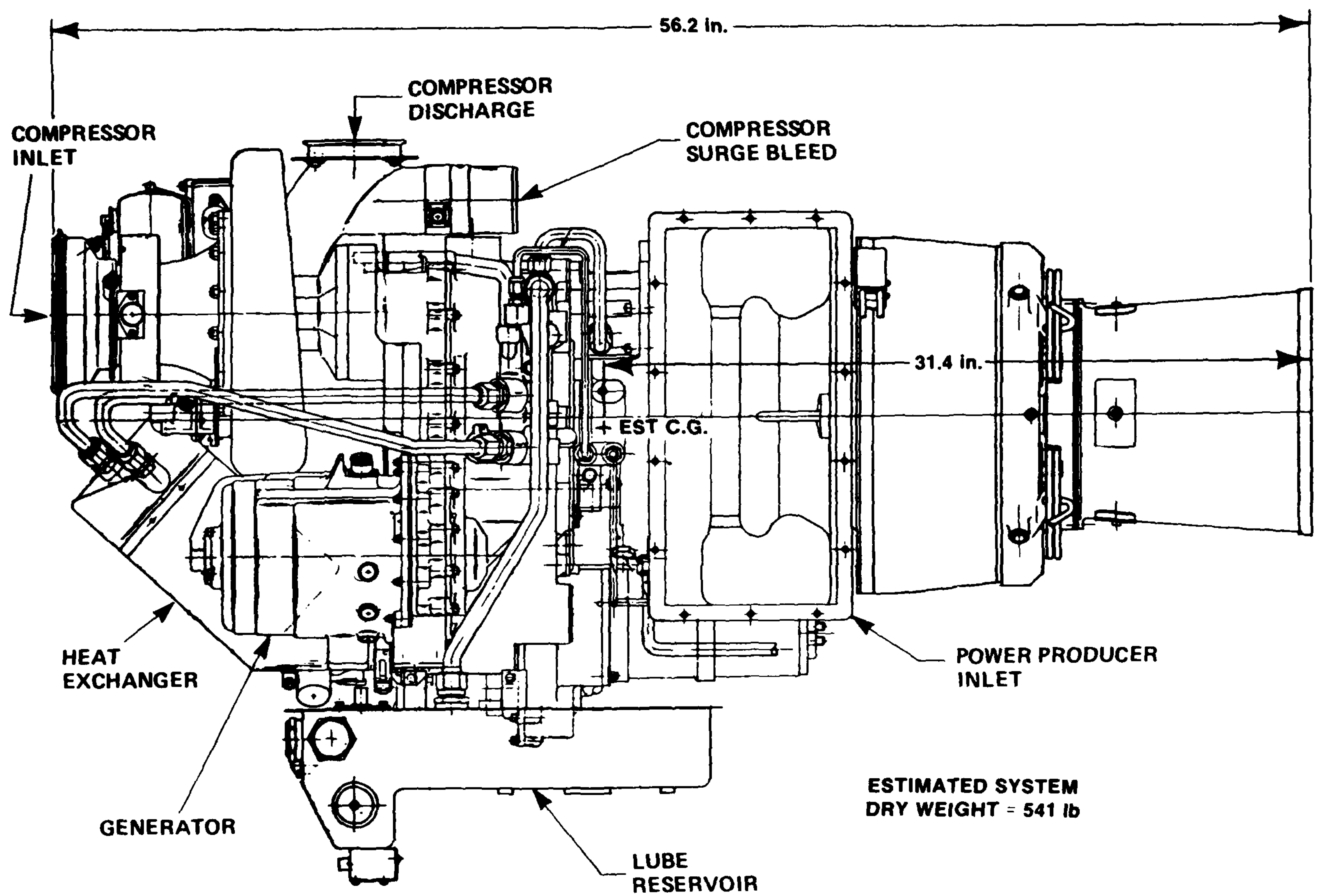


Figure 27. HPAPU - Top View.

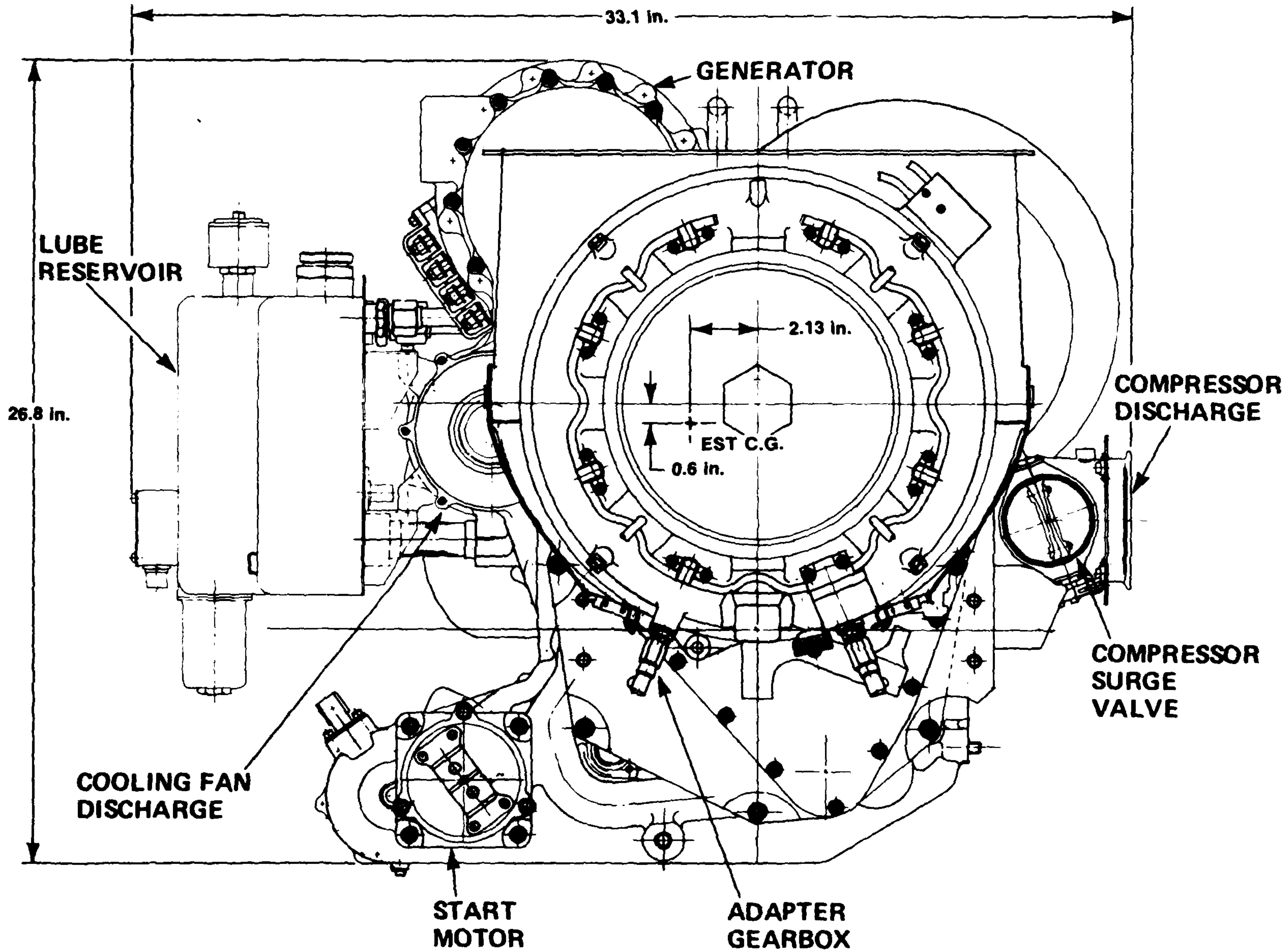


Figure 28. HPAPU - Rear View.

Adapter Gearbox

The adapter gearbox provides the interface between the Avco Lycoming high-performance power producer and the Sundstrand accessory gearbox. Separate power and accessory gear trains are provided within the gearbox to produce the proper speed and direction of rotational inputs to the accessory gearbox.

A Gerotor-type pump that provides oil scavenge for the Lycoming power producer is mounted on the adapter gearbox. Scavenge oil from the adapter gearbox is gravityfed into the accessory gearbox. The adapter gearbox is vented to the unpressurized accessory gearbox.

The power gear train comprises gear numbers 1 through 3 as shown in the gear schematics (Figures 29 and 30). These gears are helical. Profile modifications and crowning are appropriately used to accommodate tooth deflections and to avoid end loading. Basic gear data are presented in Tables 3 and 4.

The accessory gear train is made up of gears 4 through 11 as shown in the gear schematics (Figures 29 and 30). The gears are spur-type with 20-degree pressure angle and 20 diametral pitch. Basic gear data for the accessory gear train are presented in Tables 3 and 4.

The adapter gearbox contains both ball and roller bearings. All bearings are tolerance Class 5 and are sized for greater than 2500 hours B-10 life. Bearing numbers correspond to the numbers shown on the bearing schematic, Figure 31. Basic bearing data are presented in Tables 5 and 6. Bearing numbers 1A and 1B are the same configuration used in the Avco Lycoming LTS 101 series engines. Bearing liners are used throughout the adapter gearbox.

The adapter gearbox housing is machined from 6061 - T3 aluminum. All gears are fabricated from vacuum-melt AMS6265 steel and are carburized, hardened, and ground.

Accessory Gearbox

The accessory gearbox, an existing Sundstrand design that was developed for another APU application, provides the attachment points for the APU components and also provides the principle mounting points for the HPAPU Demonstrator system.

The accessory gearbox contains two gear trains:

1. The power gear train drives the load compressor, generator, and cooling fan.

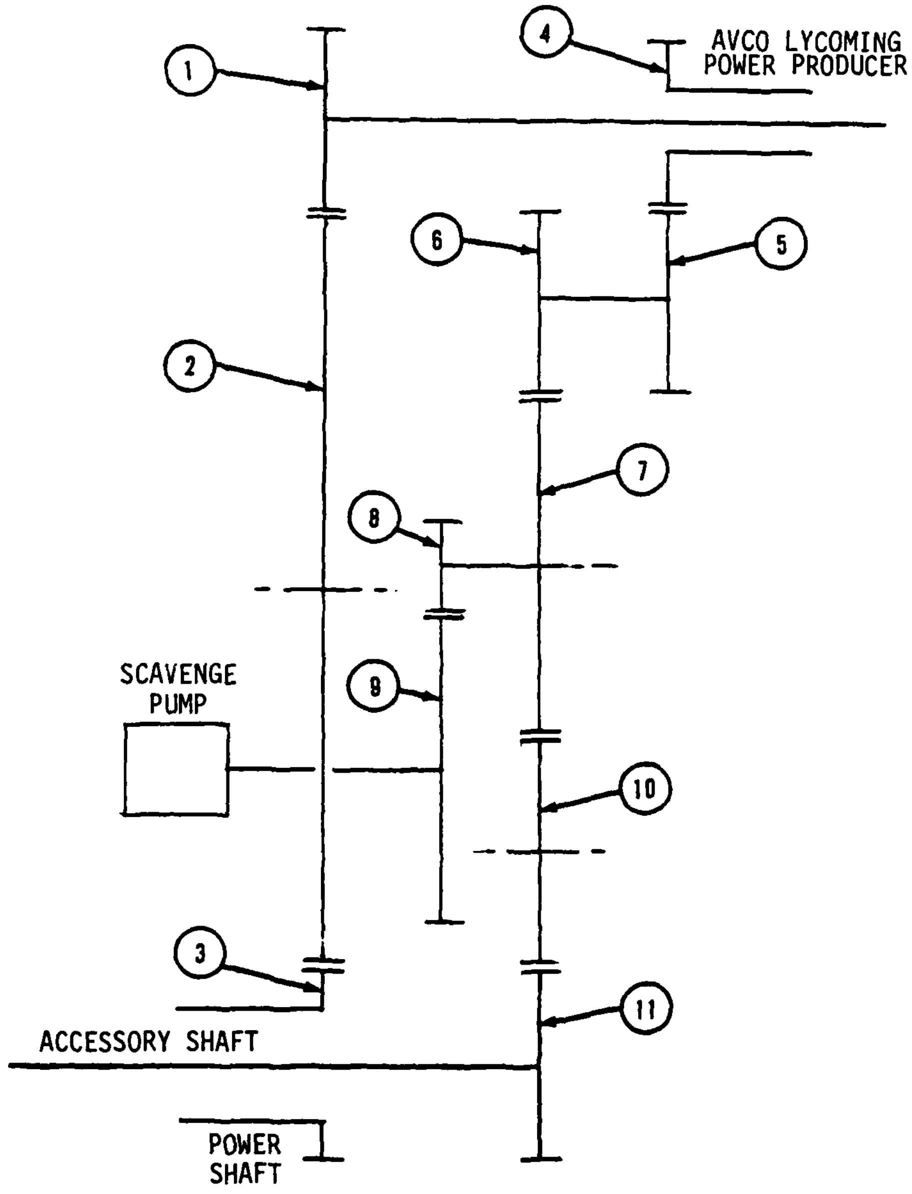


Figure 29. Adapter Gearbox Gear Schematic - Power and Accessory Train.

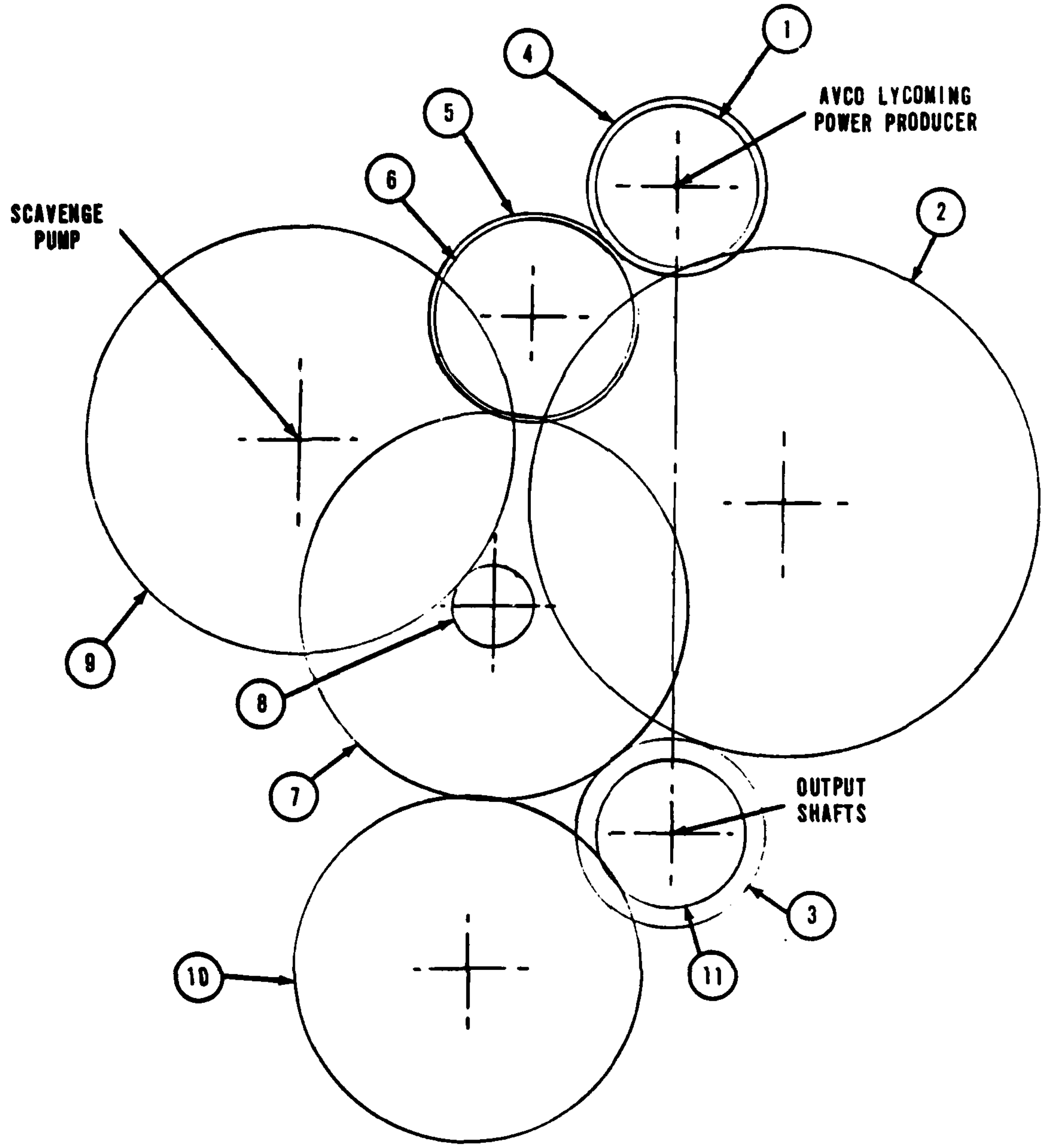


Figure 30. Adapter Gearbox Gear Schematic - Power and Accessory Train.

TABLE 3. ADAPTER GEARBOX GEARING DATA

Gear No.	No. Teeth	Pitch Dia.(in.)	Face Width(in.)	Speed (rpm)	Helix Angle(deg)	Dia. Pitch	Press Angle(deg)
1	32	1.802	1.428	37,000	13.33	18.249	22
2	115	6.4762	1.188	10,296	13.33	18.249	22
3	39	2.1963	1.125	30,359	13.33	18.249	22
4	40	2.000	0.34	48,000	-----	20	20
5	49	2.450	0.25	39,184	-----	20	20
6	45	2.250	0.32	39,184	-----	20	20
7	90	4.500	0.25	19,592	-----	20	20
8	20	1.000	0.25	19,592	-----	20	20
9	96	4.800	0.18	4082	-----	20	20
10	81	4.050	0.32	21,769	-----	20	20
11	35	1.750	0.25	50,379	-----	20	20

TABLE 4. ADAPTER GEARBOX GEAR LIFE SUMMARY

Gear No.	Speed (rpm)	Mean Torque (in./lb)	G-10 Lives (hr) Hertz	Bending
1	37,000	755	22,291	100,000
2	10,296	2,713	80,109	100,000
2	10,296	2,713	80,109	100,000
3	30,359	920	42,340	100,000
4	48,000	16	100,000	100,000
5	39,184	20	100,000	100,000
6	39,184	20	100,000	100,000
7	19,592	40	100,000	100,000
8	19,592	6	100,000	100,000
9	4,082	29	100,000	100,000
7	19,592	40	100,000	100,000
10	21,769	35	100,000	100,000
10	21,769	35	100,000	100,000
11	50,379	15	100,000	100,000

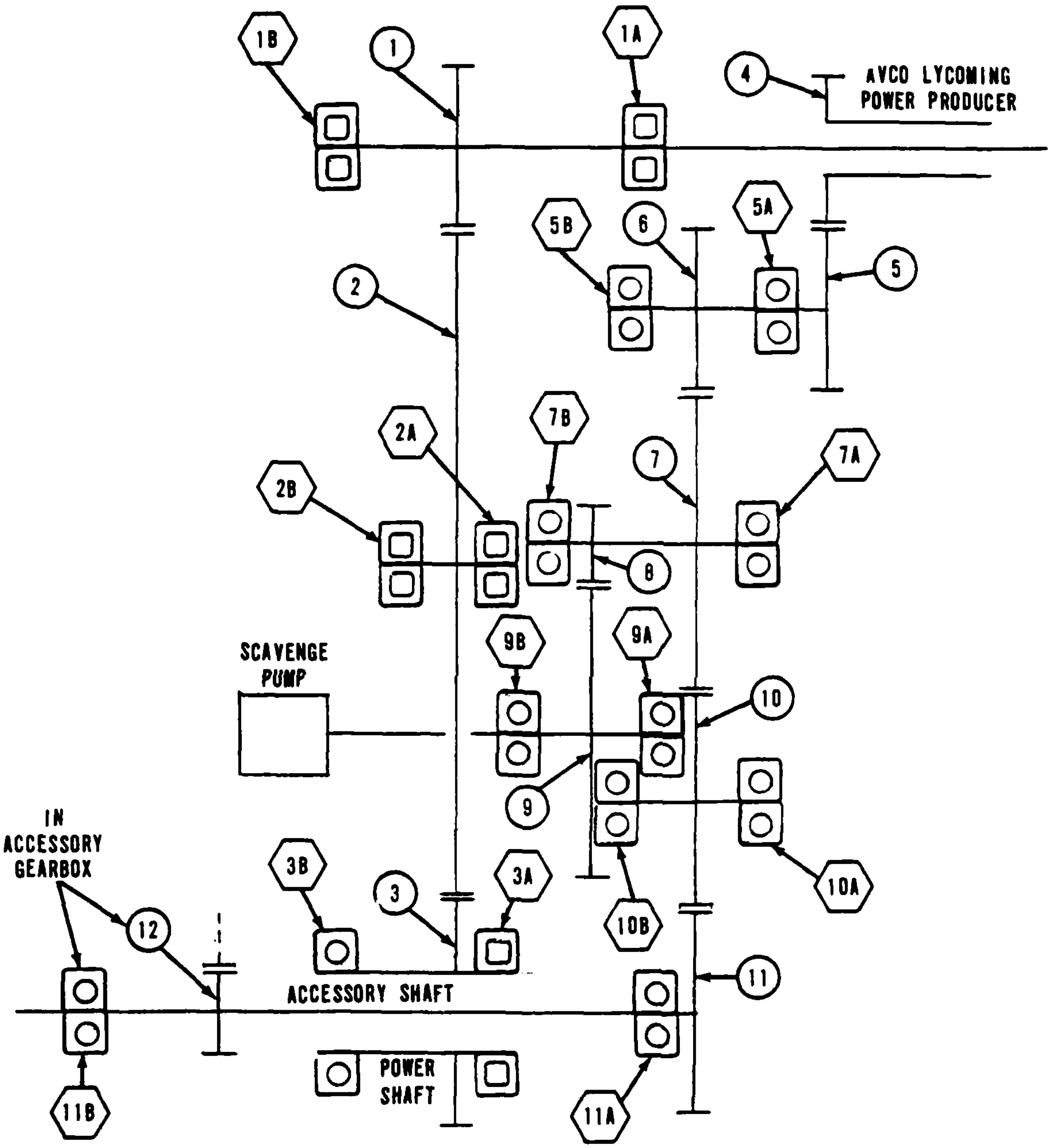


Figure 31. Adapter Gearbox Bearing Schematic.

TABLE 5. ADAPTER GEARBOX BEARING DATA

Bearing No.	Size No.	Bearing Type	CEVM Material	Dynamic Capacity (lb)	Max. Speed (rpm)
1A	206	Roller	52100	8400	37,000
1B	206	Roller	52100	8400	37,000
2A	307	Roller	52100	13500	10,296
2B	207	Roller	52100	13500	10,296
3A	109	Roller	52100	8500	30,359
3B	111	Ball	52100	5300	30,359
5A	201	Ball	52100	1200	39,184
5B	201	Ball	52100	1200	39,184
7A	104	Ball	52100	1630	19,592
7B	104	Ball	52100	1630	19,592
9A	201	Ball	52100	1200	4,082
9B	104	Ball	52100	1630	4,082
10A	104	Ball	52100	1630	21,769
10B	104	Ball	52100	1630	21,769
11A	007	Ball	52100	2049	50,379
11B	106	Ball	52100	2260	50,279

TABLE 6. ADAPTER GEARBOX BEARING DATA - B10 LIFE

Bearing No.	Speed (rpm)	Load (lb)	B-10 Life (hr)
1A	37,000	271	62,990
1B	37,000	557	7,797
2A	10,296	864	62,000
2B	10,296	1,224	26,000
3A	30,359	522	12,634
3B	30,359	653	2,668
5A	39,184	75	3,113
5B	39,184	10	10^4
7A	19,592	43	10^4
7B	19,592	10	10^4
9A	4,082	11	10^4
9B	4,082	23	10^4
10A	21,769	13	10^4
10B	21,769	7	10^4
11A	50,379	46	28,074
11B	50,379	34	24,200

2. The accessory gear train drives the fuel pump and integral lubrication and scavenge pumps. The starter motor is connected to the accessory gear train through an overrunning clutch.

Integral to the accessory gearbox is a single-stage, axial-flow, cooling fan that draws air through the air-oil heat exchanger to provide cooling for the lubrication system.

Load Compressor

The load compressor is a Sundstrand-developed, single-stage, centrifugal, 3.8:1 pressure ratio machine operating at a constant speed of 47,200 rpm. Variable inlet guide vanes are used to modulate flow according to pneumatic demand, and a vaned diffuser is used to achieve flow range and high efficiency. A bleed valve is incorporated to control compressor surge.

Actuation of both the variable inlet guide vanes and the surge bleed valve is provided by power producer bleed air supplied to pneumatic actuated cylinders. Supply air for actuation of both systems is modulated by individual servo valves.

Prior to use on the HPAPU, Sundstrand load compressor experience was in excess of 350 hours of testing. This testing included over 100 hours on the compressor configuration used in the HPAPU Demonstrator system.

Generator

HPAPU electrical power is supplied by a Sundstrand Model 60EG01 generator. This generator is a 400 Hz, 60/75 VKA, 4-pole, 12,000 rpm, self-excited, brushless synchronous machine. The unit is rated at 75 KVA continuous operation with overload rating of 90 KVA for 5 minutes. Spray oil cooling is provided via the accessory gearbox.

Again, prior to use in the HPAPU, Sundstrand had accumulated extensive test experience with this generator. In-house test time was in excess of 169,000 hours, with the hightime unit at nearly 16,000 hours. Ten units had in excess of 10,000 hours of test time. Four units, then operating in commercial service, had accumulated over 3000 hours.

Starter Motor

The starter motor is a four-pole, series-wound, direct-current machine designed and manufactured by Sundstrand. Starter current is supplied from a stand-mounted storage battery system.

Figure 32 shows the HPAPU torque required for starting and the available starter motor torque at sea level standard-day conditions. Sundstrand experience with this starter in a similar application had produced more than 80 successful APU starts without incident.

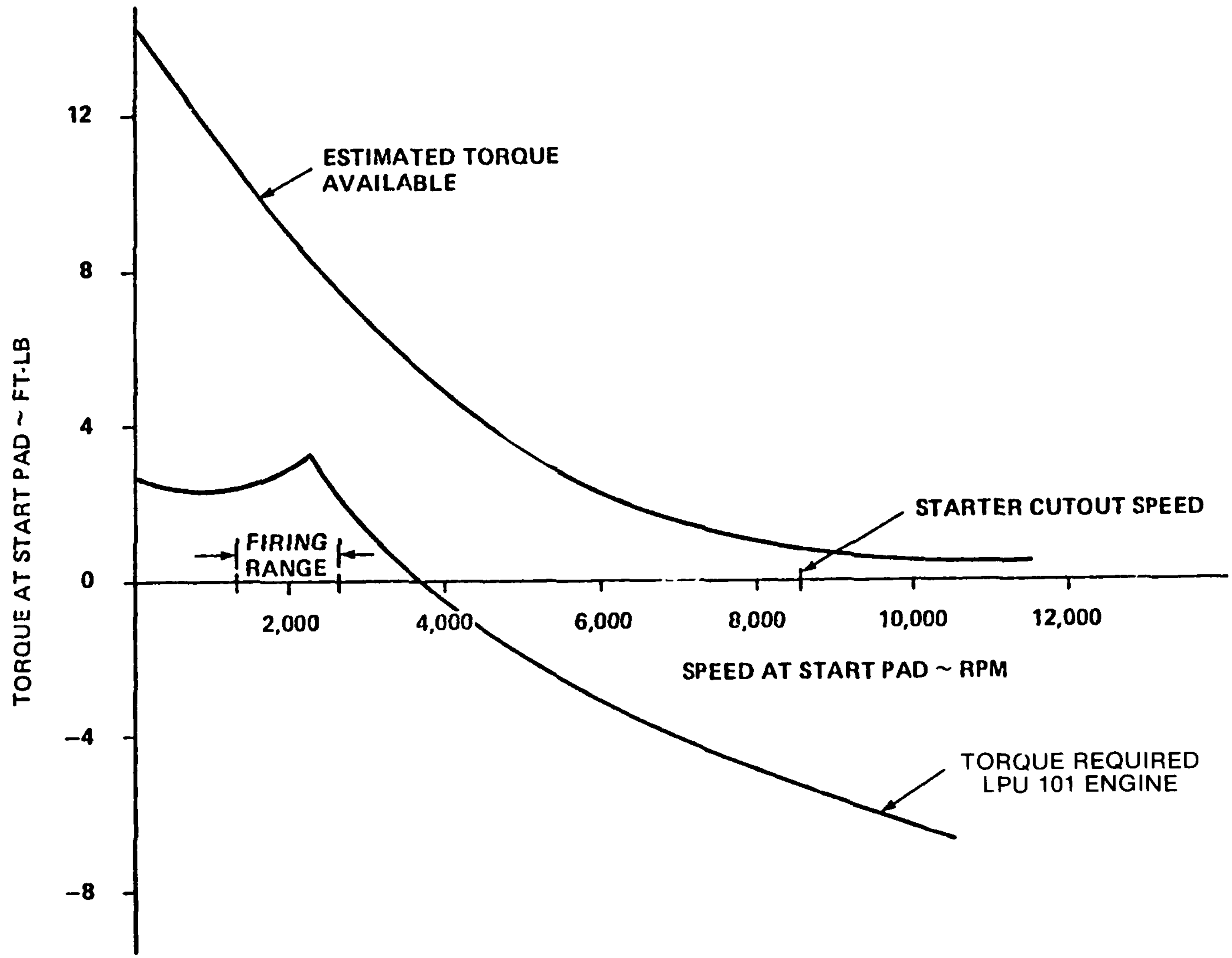


Figure 32. HPAPU Start Characteristics - Tam = 59°F.

Lubrication System

Figure 33 is a schematic of the HPAPU lubrication system. An external oil reservoir is used to feed the lubrication pump. Oil is pumped through the air-oil heat exchanger prior to entering the accessory gearbox and HPAPU components.

Lubrication for the load compressor bearings is supplied from the accessory gearbox through the hollow compressor drive shaft.

Lubrication and Scavenge Pumps

The lubrication pump and scavenge pumps, which are integral to the accessory gearbox, are vane-type units of Sundstrand design. The lubrication pump is rated at 250 psi and 15 gal/min. The main scavenge pump is rated at 18 gal/min, and the generator scavenge pump at 4 gal/min. The lubrication and scavenge pumps are contained in a single housing and driven from a common gearshaft.

Oil Reservoir

The external oil reservoir contains a swirl chamber de-aerator and attached lubrication filter and is equipped with sight gages and a low-oil quantity indicator switch. Indicated lubrication levels are as follows:

Upper sight gage	10.4 quarts
Lower sight gage	8.4 quarts
Low level indicator	6.8 quarts

The reservoir is also equipped with a pressure fill port, a gravity fill port, and a differential pressure indicator.

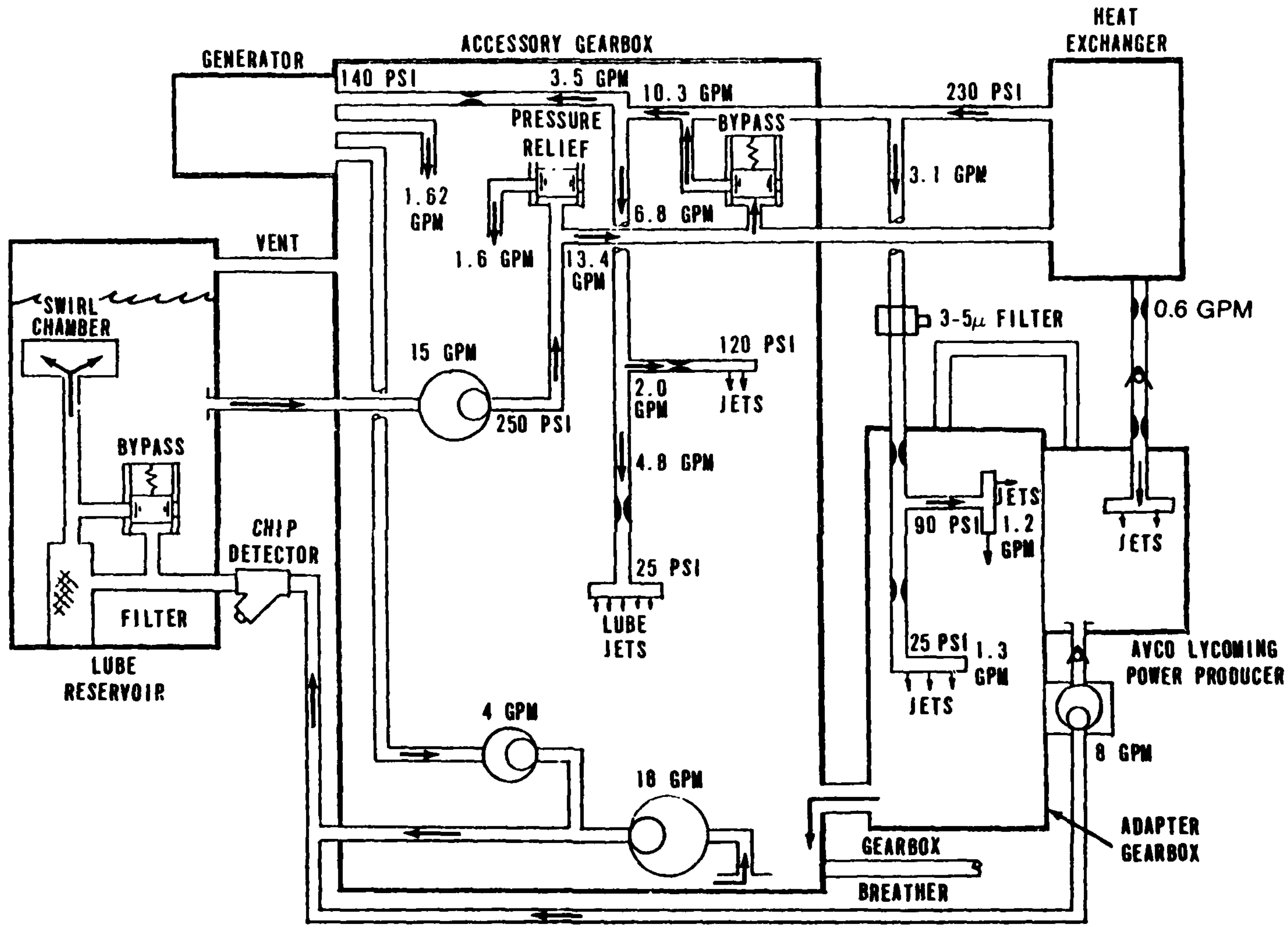


Figure 33. HPAPU Lubrication System.

Heat Exchanger

The heat exchanger is a two-pass oil, single-pass air cooler with a frontal area of 60 square inches and depth of 4.25 inches. The design parameters for a 130°F, sea level day are as follows:

Oil Side

Flow rate (m)	94 lb/min
Oil temperature in ($T_{oil}in$)	268°F
Oil temperature out ($T_{oil}out$)	229°F
Heat rejected (Q Rej)	1900 Btu/min

Fin stock 15 layers, lanced offset, 18.5 fins/in., 0.100 in. fin height, 1/8 lanced length, aluminum

Air Side

Flow rate (m)	80 lb/min
Air temperature in ($T_{air}in$)	132°F
Air temperature out ($T_{air}out$)	231°F

Fin stock 16 layers, 3/8 wavy, 18 fins/in.
0.250 in. fin height, 0.006 thick, 0.078 offset, aluminum

The above parameters reflect the "worst case" operating conditions. Operation at test cell ambient conditions results in lower air and oil temperatures through the heat exchanger.

Electronic Controller

The Sundstrand electronic analog controller, in conjunction with the fuel control and a proportional solenoid, provides operational control of the HPAPU. Automatic start and shutdown sequences for the power producer are programmed into the controller, along with necessary safety and shut-down functions at each sequence stage. Shutdown is also initiated during operation in the event of engine overspeed, overtemperature, and low oil pressure or high oil temperature. The controller senses generator output frequencies and governs the power producer speed to hold generator frequency within predetermined limits.

Using the input from transducers located at the load compressor, the controller monitors operating pressures and airflow. With reference to a programmed surge line, the controller modulates the position of a surge bleed valve and maintains compressor operation in a stable region. It also regulates the action of the compressor inlet guide vanes, depending on the required air flow.

Fuel Control System

The fuel control for the LPU 101-700 engine is a conventional Bendix pneumatic/ mechanical control, designated the PPZ1. It controls the start and acceleration flow, deceleration flow, maximum gas generator speed, and idle speed. The speed input is a 4,200 rpm drive from the fuel pump.

Interface with the Sundstrand electronic control is a proportional solenoid acting upon a pneumatic pressure line (called Py pressure).

The fuel pump is a Sundstrand positive-displacement gear pump, P/N 5004506.

SECTION III

TEST AND DEMONSTRATION

3.1 BACKGROUND

Phase III of the HPAPU program consisted of the procurement and manufacture of system details, preparation of dedicated test facilities, and assembly and test of two HPAPU systems.

The test program was divided into two sections. The power producer of the first system, assembled to an aircraft-type turboshaft gearbox, was subjected to environmental testing at Avco. The power producer was also assembled to an HPAPU system and subjected to 10 simulated main engine starts at the Sundstrand test facility.

After acceptance testing at Avco, the second power producer was assembled to a second HPAPU system and subjected to endurance testing at Sundstrand.

3.2 ENVIRONMENTAL TESTING

The power producer environmental testing conducted at Avco Lycoming was accomplished on engine S/N 201 using a standard Lycoming LTS 101-600A accessory gearbox and an LTCT2040 waterbrake for power absorption. Simulated main engine starts were conducted at the Sundstrand facility, Rockford, Illinois, and featured the entire auxiliary power unit, complete with load accessories and automatic controller.

Sea level environmental testing was conducted in accordance with the Air Force approved Test Plan LYC78-27, dated 26 May 1978. Engine S/N 201 was assembled for testing per Parts List 4-005-000-01 as amended in Test Assembly Memoranda 8530-003, dated 22 November 1978. The engine hardware had previously accumulated 12.18 hours of operation during preliminary checkout testing.

Altitude environmental testing was conducted in accordance with the Air Force approved Test Plan LYC78-48, dated 7 November 1978. The engine was assembled for testing in accordance with Parts List 4-005-000-01, as amended in Test Assembly Memoranda 9530-005, dated 21 February 1979. The engine hardware had previously accumulated 44.46 hours of operation during checkout and sea level environmental testing.

Test Equipment

The following test equipment and apparatus were used during performance of the environmental and peak-power demonstration testing.

Power Absorption

Power absorption was accomplished with an Avco Lycoming Mo‹ LTCT-2040 waterbrake. The waterbrake was supported by means of a calibrated strain-gauged beam support that is used to measure output shaft torque.

Airflow Measurement

Engine airflow was measured with a calibrated inlet nozzle assembly, P/N TE27387, based on ASME recommended geometry. Static and total pressure within the nozzle throat were measured with precision transducers.

Transient Recording Equipment

Oscillographic recorders were used to measure transient characteristics versus time. The logged parameters were those detailed in the test plans.

Temperatures

Temperatures were measured with chromel-alumel (Type K) thermocouples.

Pressures

Hydraulic and pneumatic pressures were measured with precision-type pressure transducers.

Rotor Speeds

Integral monopole magnetic signal generators mounted on the LTS 101 series accessories/reduction gearbox were used to measure rotational speeds.

Fluid Flows

Fluid flows (fuel and oil) were measured with calibrated turbine flow elements.

Positions

Position indicators and associated transmitters were used to measure spindle angular positions.

Starting

Starting torque and current were measured (for official starting demonstrations with electric starter) with a strain-gauged starter pad adapter and a calibrated shunt. Starting power was supplied by a motor generator set or a single 22-ampere hour nickel-cadmium battery for the electric starter. A motor/pump hydraulic cart supplied the starting power for the hydraulic starter, Vickers Model P/N MF039B006B.

Vibrations

Engine case vibrations were measured with Consolidated Electrodynamics Corp. (CEC) Model 128 precision transducers in conjunction with signal conditioning circuitry incorporating a 200 Hz high pass filter network.

Lubrication System

An external oil system was the source of engine lubrication. The system consisted of a reservoir, heat exchanger, and associated plumbing. The oil system was serviced with oil conforming to Military Specification MIL-L-7808, and was subjected to the same environment as the engine.

Environmental Test Equipment

Various facilities and special test equipment were used to achieve the desired environmental conditions.

For standard and hot-day sea level test phases, the test article was installed in Lycoming Development Cell D7. Warm air was supplied by using a facility ram blower and a free-standing steam radiator.

For cold sea level testing, the test article was installed in Development Cell D8 with cold air supplied by a facility open-loop refrigeration plant.

The altitude test phase was conducted in the special test equipment chamber, P/N TE29300, which adapted cell D8 for altitude operation. The chamber is a segmented cylindrical pressure vessel with penetrations and valving for inlet air and exhaust discharge. Test Cell D8 served as its inlet plenum. The engine exhaust flow was ducted to the throat of an air-driven ejector nozzle. The ejector motive airflow was supplied by an Avco Lycoming T53 series compressor driven by a facility electric motor. The volumetric flow of the compressor was increased with a jet fuel-fired afterheater. Figures 34 and 35 depict the chamber and area arrangement.

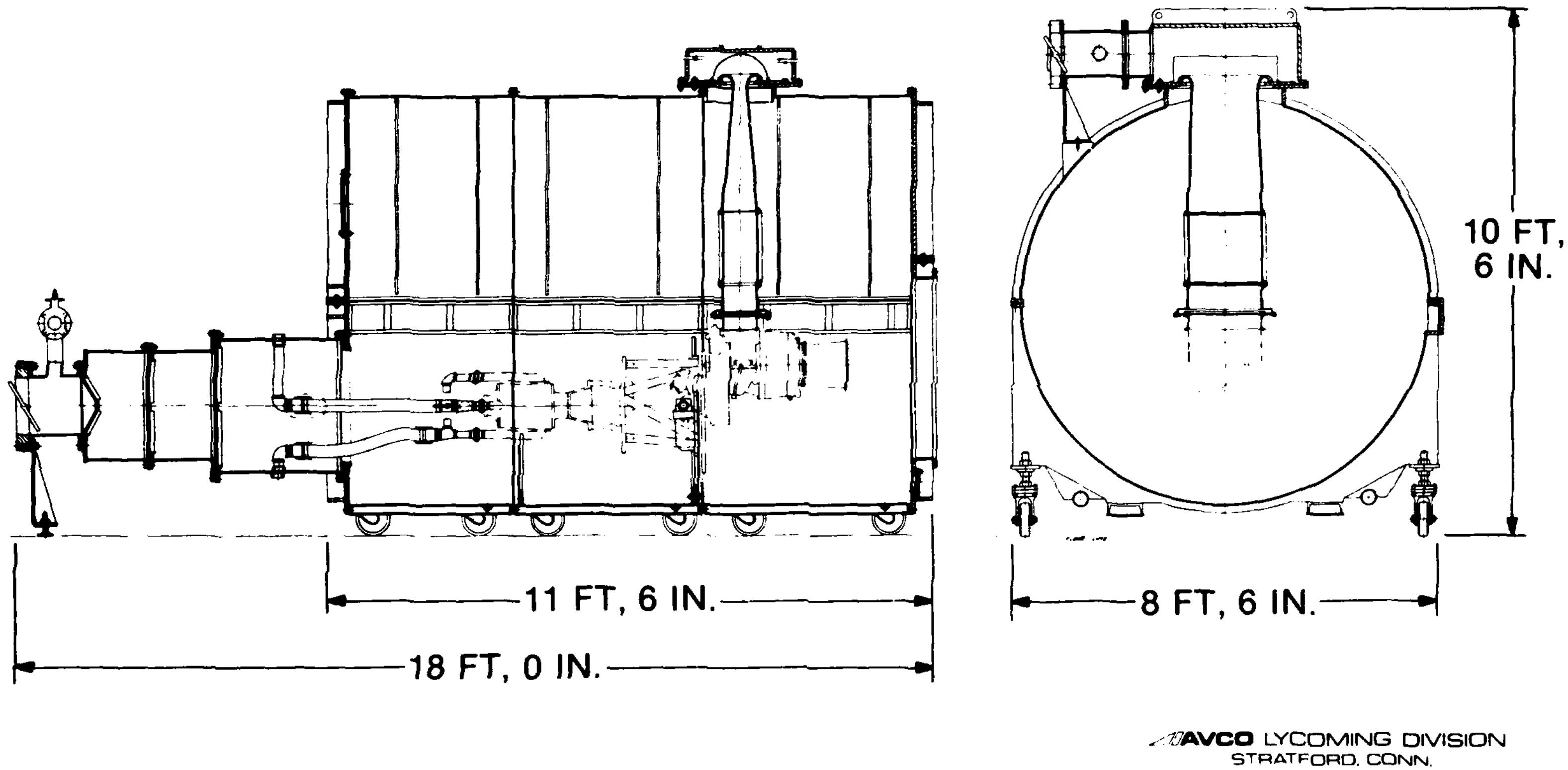


Figure 34. Altitude Test Equipment Plenum.

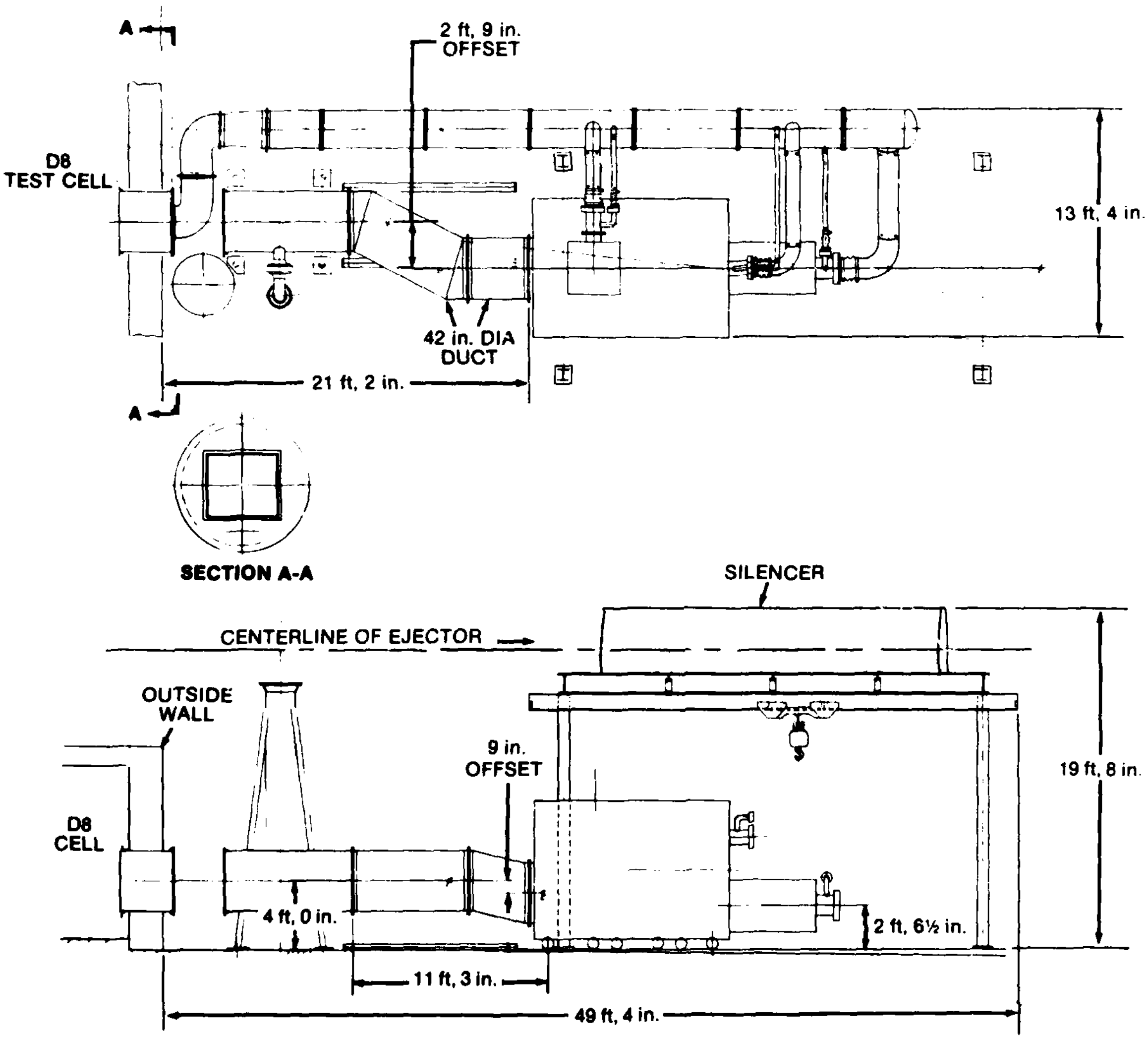


Figure 35. Area Arrangement of Altitude Facility and Test Equipment.

The ejector was operated at a steady-state inlet condition with both the engine inlet and chamber air inlet valves modulated to obtain the proper pressure conditions at the engine. To achieve the correct thermal environment, tempered air was ducted to cell D8 (inlet plenum) from the facility refrigeration plant.

Method of Test

The environmental tests conducted on the HPAPU power producer were in accordance with Air Force approved test plans, LYC78-27 and LYC78-48. The methods employed and the sequence of testing are discussed below.

The test article was installed in Lycoming Development Test Cell D7 on 14 December 1978. Following a brief mechanical checkout, a peak power demonstration consisting of 10 hours of non-interrupted operation at 456 shaft horsepower with 130-135°F inlet air temperature was conducted. Following this peak power demonstration, sea level standard day starting and performance calibrations were conducted.

The entire engine fuel and oil systems were maintained at the desired thermal condition for at least two hours prior to the initial start in each series.

Upon successful conduct of the initial start, the engine was shut down and a restart conducted within 15 minutes. This sequence of soak, initial start, shutdown, and restart was repeated twice for a total of four starts in each mode.

The performance calibration consisted of obtaining steady-state data points that were sufficient in quantity to define the aero/thermal characteristic of the engine. Transient performance was defined by conducting a series of power transients from idle to the maximum power condition. Transients were conducted from the aircraft equivalent of ground idle (50 percent gas generator speed) and flight idle (70 percent gas generator speed). By agreement between Lycoming and the Air Force, the standard day testing was conducted at the prevailing ambient condition, and the data corrected to standard conditions as defined in the U.S. Standard Atmosphere ASTIA Document 401813.

Hot-day (130°F) performance calibrations were conducted in essentially the same manner as the standard-day effort.

After the engine was returned to the Test Assembly area at the conclusion of the hot-day demonstration, the power producer hardware was subjected to a limited inspection by Lycoming Engineering and Quality and Air Force representatives. No distress was found as a result of engine operation.

At this time, the gas producer turbine was updated with C103 turbine blades that were now available. These blades have stress-rupture characteristics superior to the C101 blades that were incorporated in the previous build. This modification updated the gas producer turbine to conform with the HPAPU Bill of Material Parts List.

The engine was installed in Lycoming Development Test Cell D8 for the -65°F sea level test activity. Cold starting and performance calibrations were accomplished in the same manner as the other demonstrations (i.e., two-hour cold soak prior to initial starting and four starts in each of the three starter configurations).

Pending further altitude chamber checkout, the environmental test sequence was changed to allow demonstration of ten simulated main engine starts. This was accomplished at the Sundstrand test facility with the power producer assembled to the first HPAPU system. The system provided pneumatic power to an air turbine starter that drove an inertia test rig which simulated the starting characteristics of a Pratt and Whitney F-100 engine. These simulated starts are described in greater detail in the TEST EQUIPMENT discussion.

Upon successful completion of the simulated main engine start demonstration, the power producer was returned to Lycoming for the altitude starting and performance test phase.

Altitude testing was conducted in accordance with the approved Air Force Test Plan LYC78-48. A sea level calibration was conducted at the onset of the altitude testing. This calibration was conducted at prevailing sea level temperature and pressure conditions to serve as the baseline for the altitude effort. Altitude calibrations were conducted at 10,000, 20,000, and 25,000 feet. This was accomplished by operating the engine at a desired power point, as defined by a mechanical compressor speed and adjusting engine inlet and exhaust pressure until the desired altitude condition was achieved. The calibrations were conducted in a stepwise fashion at a constant altitude. The inlet air temperature was maintained close to the altitude standard day temperature.

Altitude starting demonstrations were conducted with an electric starter motor. A cold soaking period of at least two hours preceded each initial start. This soak period was conducted at essentially sea level pressure altitude. On completion of the cold soaking period, the chamber was brought to the desired pressure altitude before the start was initiated. As in the sea level starting demonstrations, the sequence of an initial start followed by a restart was conducted during altitude testing.

Oil and fuel used during testing conformed to MIL-L-7808 and MIL-T-5624 (JP4), respectively. Samples of both the oil and fuel were subjected to laboratory analysis. The results of these analyses proved conformance with the Military Specification.

All engine services, such as fuel and oil systems, were subjected to the same environment as the engine. By agreement between Lycoming and the Air Force, the storage battery (in the case of battery-powered starts) was subjected to the same pressure altitude as the engine but was maintained at essentially room temperature.

Alternate fuel and oil, as well as various fuel controls, were investigated during the conduct of the altitude test. These measures included starting demonstrations using electronic fuel controls and starting and performance calibrations using JP5 fuel (MIL-T-5624 Grade JP5) and 23699 oil (MIL-L-23699).

At the conclusion of the test, a posttest sea level calibration was conducted in the same manner as the pretest calibration. The engine was then returned to the Test Assembly area for detailed hardware inspection.

Upon reassembly, LPU 201, S/N E201 was installed in Lycoming Development Test Cell D2F for final acceptance testing.

Results

Avco Lycoming Model LPU 101-700, High Performance Auxiliary Power Unit power producer, S/N E-201, successfully completed a series of environmental tests including starting and performance demonstrations at the following conditions:

Altitude	Temperature
Sea Level	130°F
Sea Level	Standard (59°F)
Sea Level	-65°F
10,000 ft.	Standard (23°F)
20,000 ft.	Standard (-12°F)
25,000 ft.	Standard (-30°F)

In addition, a peak power demonstration was conducted at the sea level, 130°F day condition, consisting of 10 hours of uninterrupted running at the peak power condition.

The following paragraphs discuss the results of the environmental and peak power tests.

Peak Power Demonstration

A ten-hour peak power demonstration conducted on 20 December 1978 was completed without pause for engine or facility maintenance.

Data logged during this test were in accordance with the Test Plan, and are presented below (Table 7). As actual inlet temperature varied between 130° and 135°F, data corrected to 130°F sea level static are included in the tabulation. The power module output power data are also corrected for gearbox power losses, which amount to approximately 1.5 percent.

TABLE 7. 10-HOUR PEAK POWER DEMONSTRATION

Parameter	Demonstrated Level Min	Avg	Max	
Gas producer speed -	97.8	98.1	98.4	Actual
Ng % of 47867 RPM	97.6	97.9	98.2	Corrected to 130°F SLS
Shaft horsepower - SHP	451	452	455	Actual
	447	451	456	Corrected to 130°F SLS
	454	458	463	130°F day no gear loss
Fuel flow - W_f	282	284	286	Actual
pph	281	283	287	Corrected to 130°F SLS
Measured gas temp.	1386	1411	1429	Actual
MGT - °F	1386	1402	1419	Corrected to 130°F SLS
Inlet air temperature °F	130	133	135	Actual

These data indicate that the power producer met the basic power density requirements of the contract and also met the Lycoming predicted performance. The objective, predicted and demonstrated values are presented in Table 8.

TABLE 8. POWER PRODUCER PERFORMANCE

Parameter	Contract Objective	Lycoming Prediction	Demonstrated Value
Output Power (shp)	200 - 500	456	458
Volume Power Density (hp/ft^3)	130 Minimum	182	183
Weight Power Density (hp/lb)	1.7 Minimum	2.49	2.43
Specific Fuel Consumption (lb/hp/hr)	1.0 Maximum	0.64	0.62

Engine Volume - 2.6 Ft^3
Engine Weight - 188 lb including exhaust diffuser

Conditions:

Inlet Air Total Pressure - 29.92 in. Hg ABS
(Sea Level Standard)

Inlet Air Total Temperature - 130°F

No Gear Loss, No Installation Loss
Output Shaft Speed 37000 rpm

The difference in the predicted and demonstrated weight-power density was due to an additional 5 pounds (approximate) in engine weight resulting from an engine casting that was manufactured from a wax buildup of a standard LTS 101 component. Specific tooling for the HPAPU will rectify this condition and elevate the weight power density to the predicted level.

The cycle temperatures demonstrated during this test did not exceed the maximum continuous field limit temperature of the certified aircraft version of this engine.

Oil consumption was monitored throughout the peak power demonstration and found to be negligible.

Mechanical performance parameters (oil pressures, engine case vibration levels, etc.) remained both stable and within established pretest tolerances throughout the 10-hour test.

Sea Level Starting and Performance Calibrations

Standard Day

On 3 January 1979, a sea level, standard day, steady-state performance calibration was conducted. The results of this calibration, graphically presented in Figures 36 and 37, indicate that the engine met or exceeded all performance predictions for this engine model. The depicted power levels are gross values that include gear losses (approximately 1.5 percent) of the LTS-101 gearbox. The graphics reflect standard-day (50°F, 29.92 in. Hg) performance of the engine.

Transient performance was determined by conducting two power transients from both ground and flight idles (approximately 50 and 70 percent gas producer speed). Results of these transients indicate that the engine achieved 95 percent of the power change within 6.85 and 2.65 seconds, respectively. Oscillographic records of these transients were taken. Figure 38 is representative of a typical transient.

Sea level standard day starting (Table 9) was demonstrated by conducting a series of initial starts (preceded by a two-hour soak period) and restarts (start conducted within 15 minutes of shutdown). Starts were conducted with an electric starter motor powered by either a battery or motor generator power source and with a hydraulic starter.

TABLE 9. SEA LEVEL STANDARD DAY STARTING DEMONSTRATION

Type of Start	Starter Type and Power Source	T Ambient (°F)	Max. MGT (°F)	Max. MGT (°F) Time to Idle (secs)
Initial	Electric MG	70	1015	21.5
Restart	Electric MG	68	1258	18.7
Initial	Electric MG	43	963	22.0
Restart	Electric MG	38	1230	19.8
Initial	Electric Batt.	38	1276	22.6
Restart	Electric Batt.	37	1414	22.0
Initial	Electric Batt.	48	1277	21.7
Restart	Electric Batt.	41	1363	21.4
Initial	Hydraulic	73	1100	18.0
Restart	Hydraulic	73	1334	17.2
Initial	Hydraulic	43	1039	19.8
Restart	Hydraulic	42	1236	17.0

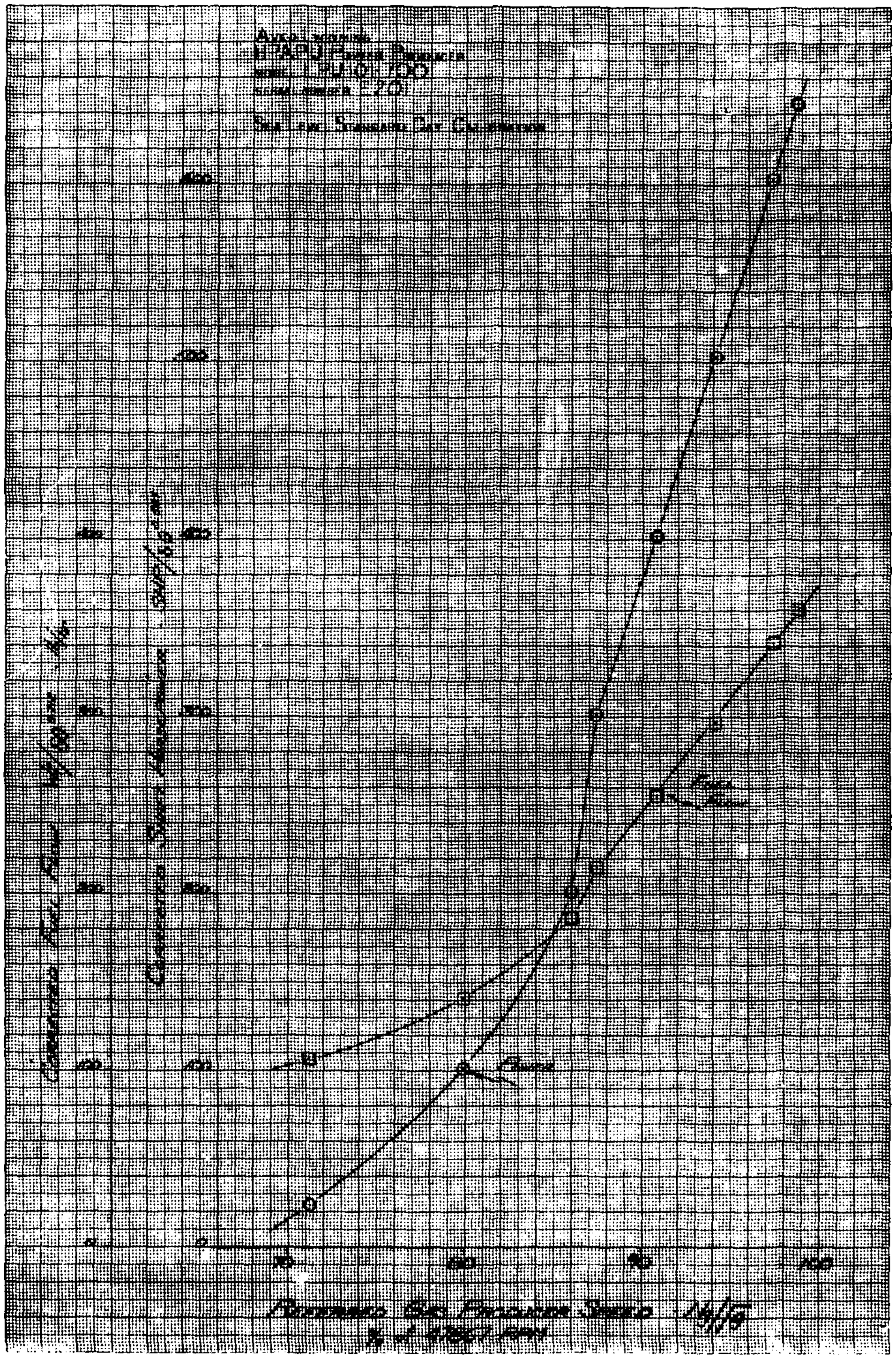


Figure 36. Referred Gas Producer Speed Versus Corrected Fuel Flow and Corrected Shaft Horsepower

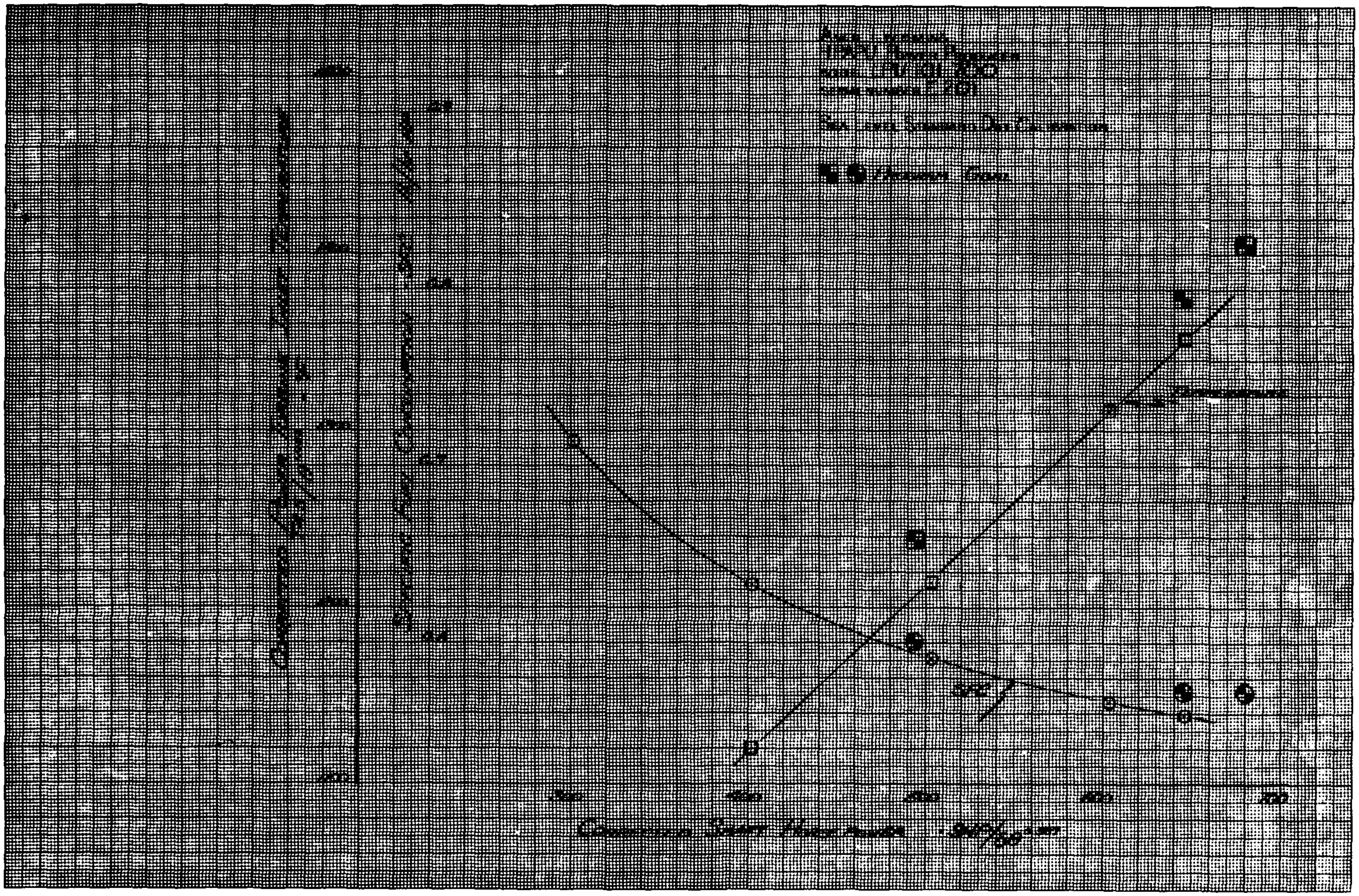


Figure 37. Corrected Shaft Horsepower Versus Corrected Power Turbine Inlet Temperature and Specific Fuel Consumption.

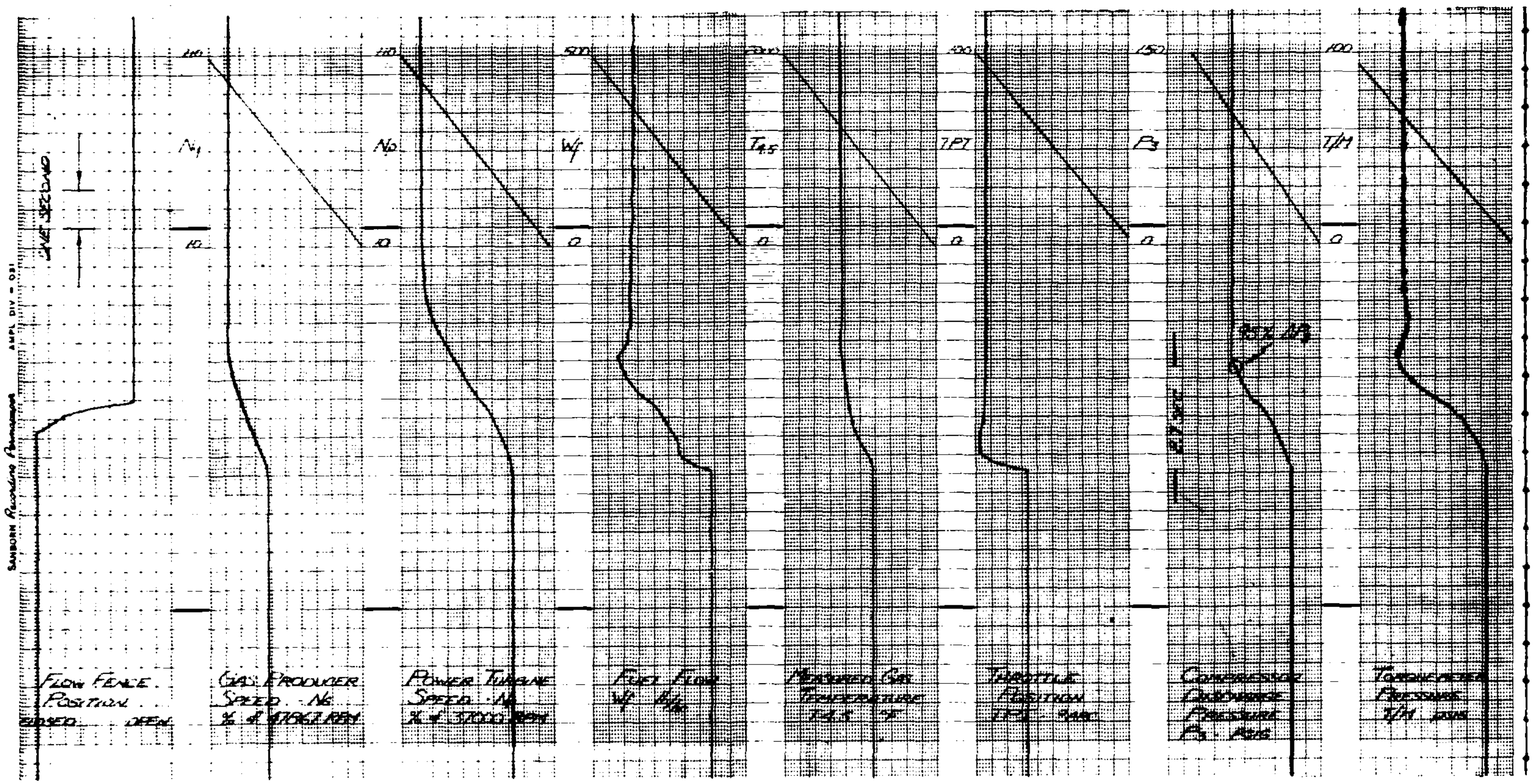


Figure 38. Transient - Flight Idle to Peak Power - Standard Day.

Representative oscillographic records of the sea level standard day starting characteristics are included as Figures 39 thru 43. These figures are also representative of starts at -65° and 130°F. The "Time to Idle" and "Max. MGT" will vary; but these variations are tabulated in the appropriate starting demonstration tables.

All starts conducted at the sea level standard condition were free from excessive measured gas temperature or objectionable compressor roughness. All starts were conducted well within the maximum allowable time of 60 seconds as defined in Military Specification MIL-P-8686 (ASG).

Hot Day (130°F)

Results of the steady-state performance calibration graphically presented in Figures 44 and 45 indicate that the engine again met or exceeded performance predictions. Depicted power levels are corrected for the 1.5 percent (approximate) gearbox loss. The data reflect the hot-day sea level (130°F, 29.92 in. Hg) performance of the engine.

Transient performance was again determined by conducting several power transients from ground and flight idle to peak power. These data, typically presented in Figure 46 indicate that the engine achieved 95 percent of the power change within 9.1 and 3.5 seconds, respectively. Transients were free of any objectionable combustion roughness or compressor instability.

Results of the sea level hot-day starting demonstration are shown in Table 10 below.

TABLE 10. SEA LEVEL HOT-DAY STARTING DEMONSTRATION

Type of Start	Starter Type and Power Source	T Ambient (°F)	Max. MGT (°F)	Max. MGT (°F) Time to Idle (secs)
Initial	Hydraulic	148	1429	18.1
Restart	Hydraulic	146	1651	19.3
Initial	Hydraulic	144	1393	20.1
Restart	Hydraulic	145	1630	18.3
Initial	Electric Batt.	143	1122	30.0
Restart	Electric Batt.	140	1400	27.9
Initial	Electric Batt.	139	1165	28.4
Restart	Electric Batt.	137	1293	26.8
Initial	Electric MG	143	1294	23.7
Restart	Electric MG	143	1380	23.9
Initial	Electric MG	140	1113	24.8
Restart	Electric MG	141	1215	25.0

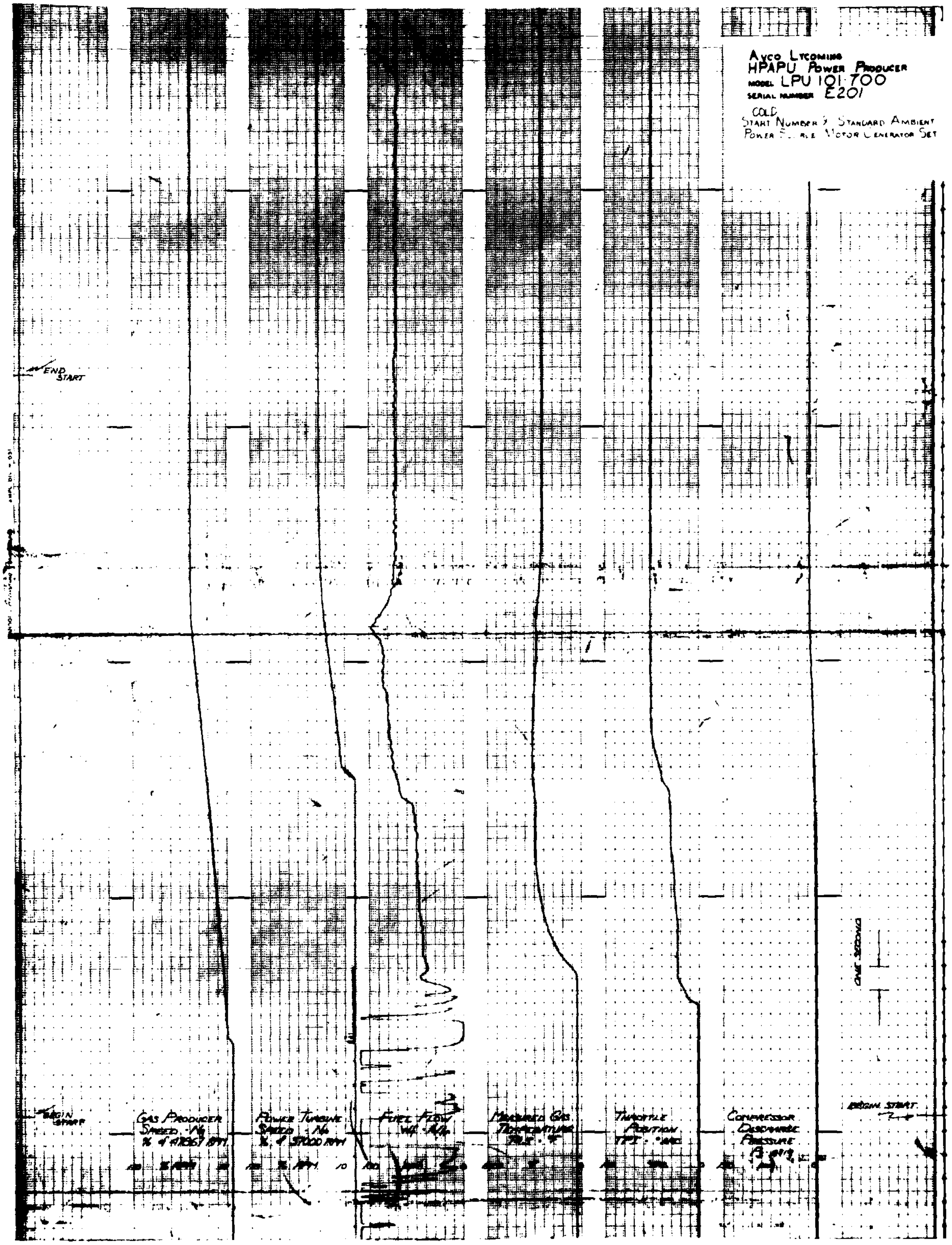


Figure 39. Motor Generator Cold Start No. 9 - Standard Ambient.

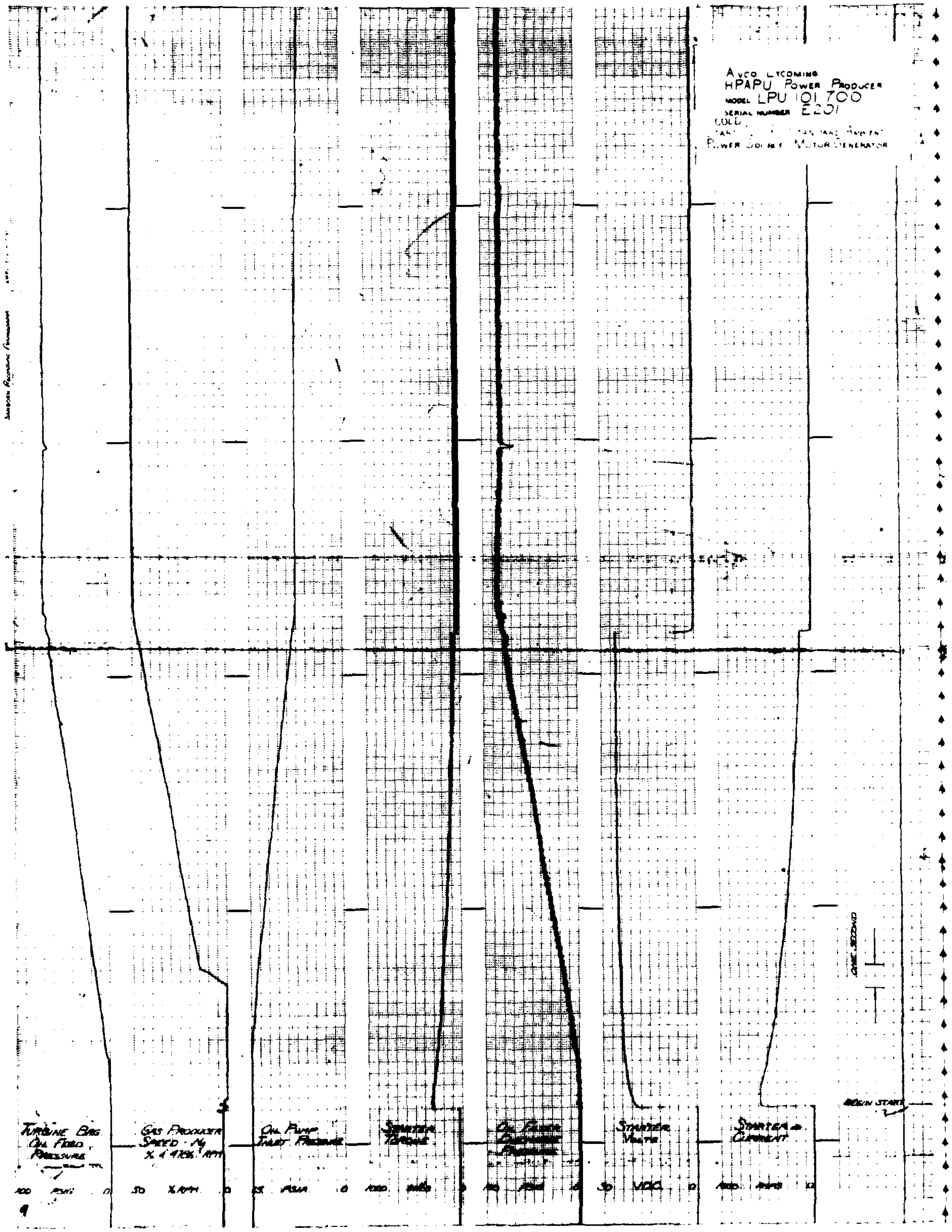


Figure 40. Motor Generator Cold Start No. 9 - Typical Data.

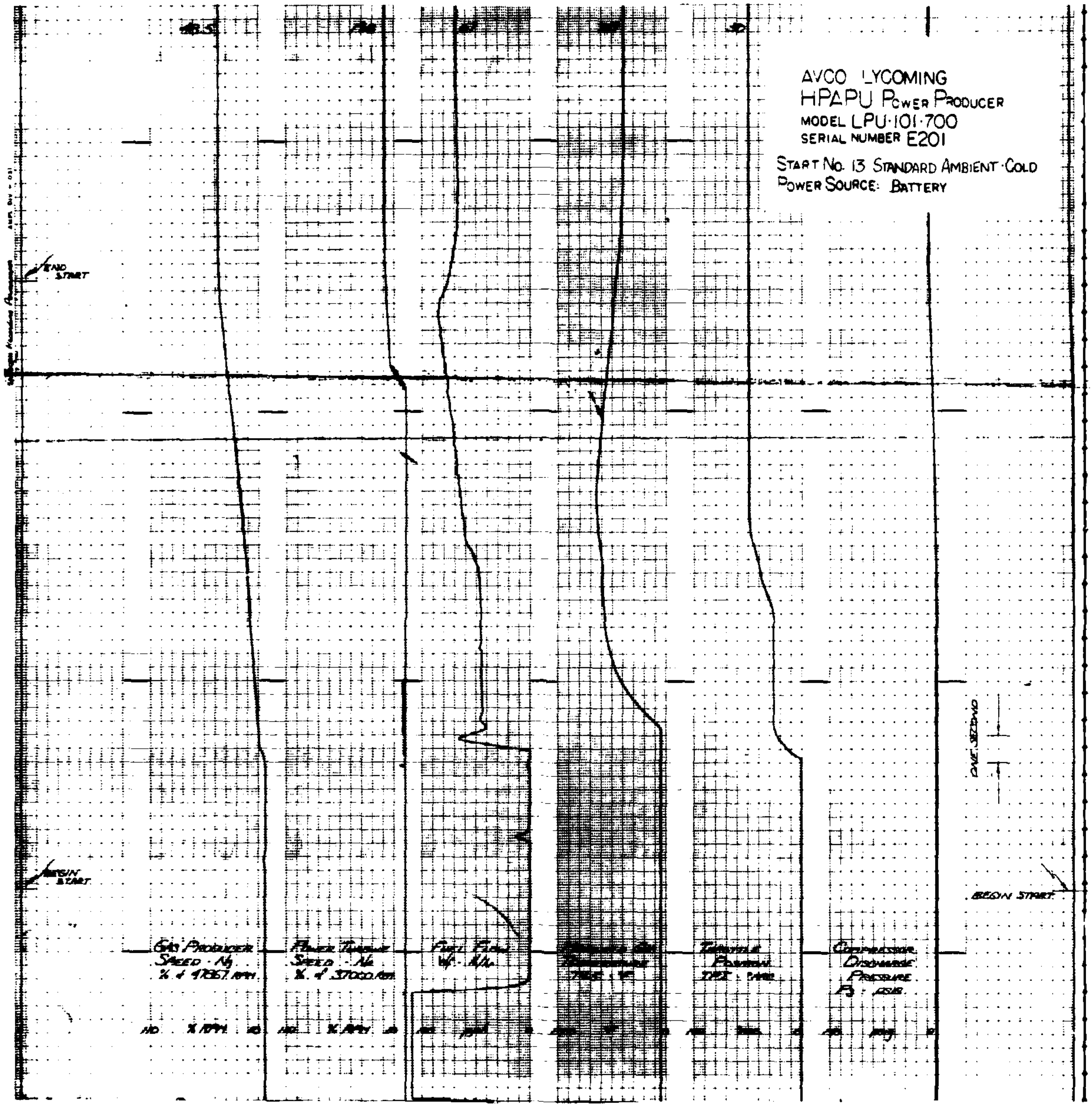


Figure 41. Battery Cold Start No. 13 - Standard Ambient.

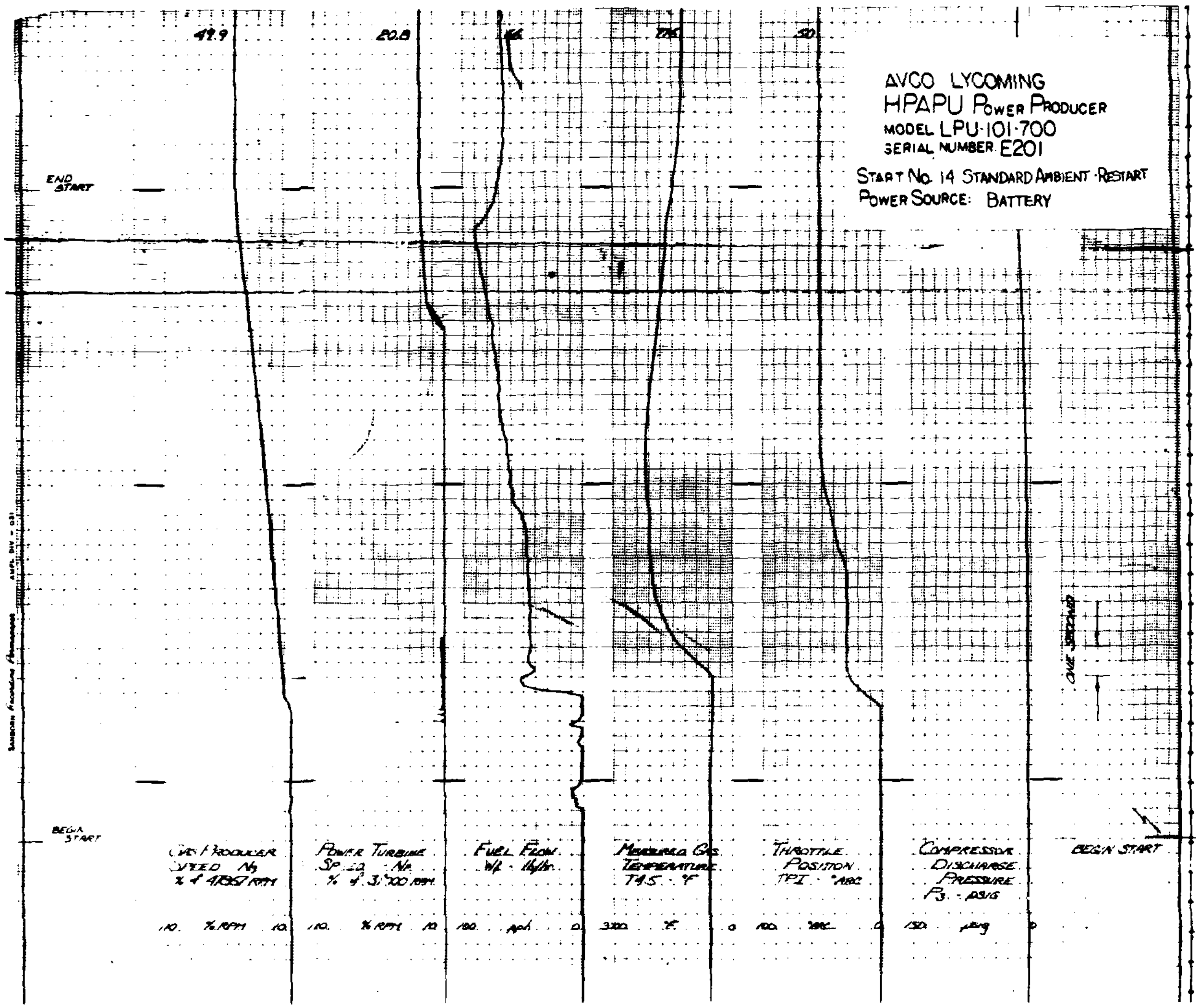


Figure 42. Battery Restart No. 14 - Standard Ambient.

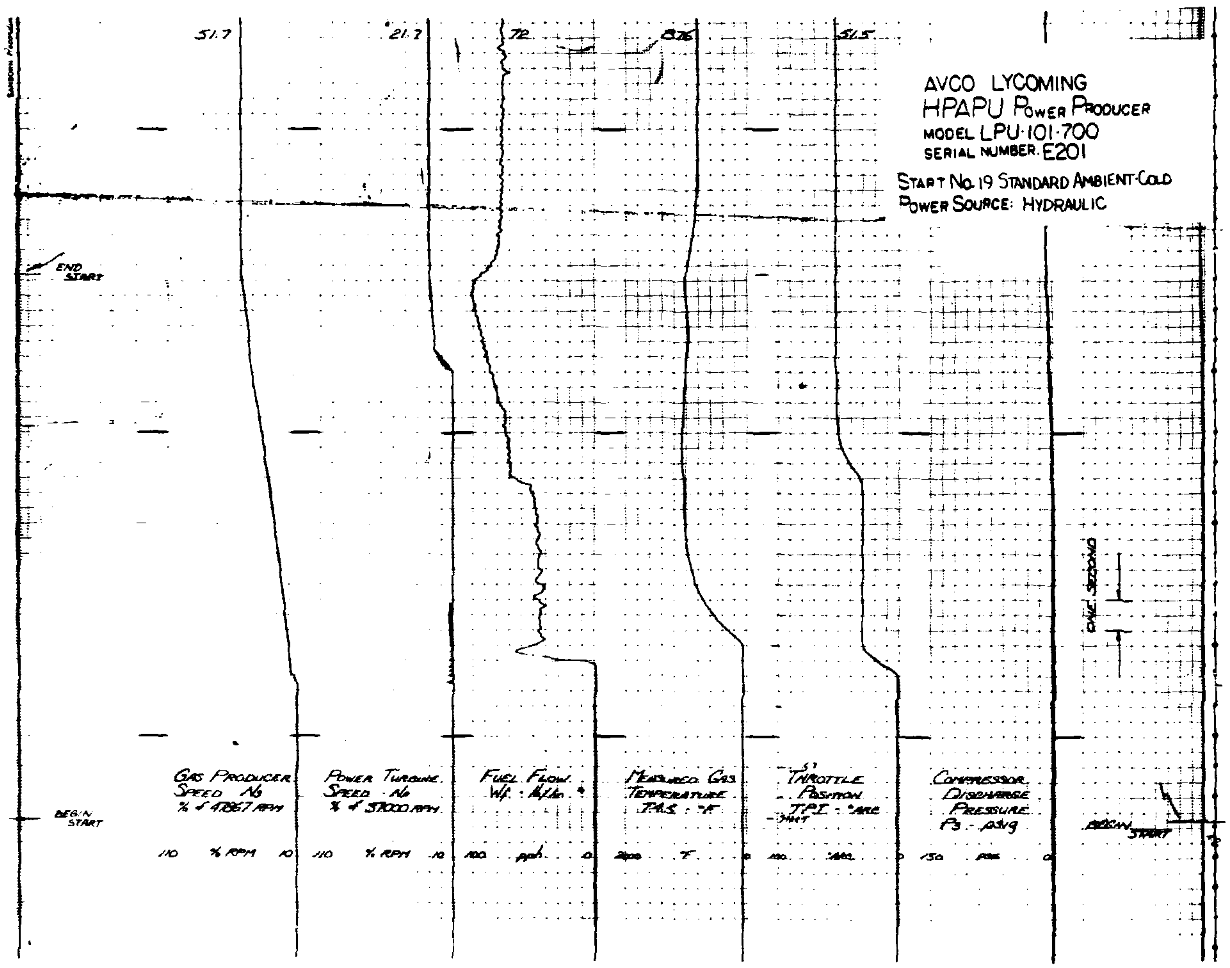


Figure 43. Hydraulic Cold Start No. 19 - Standard Ambient.

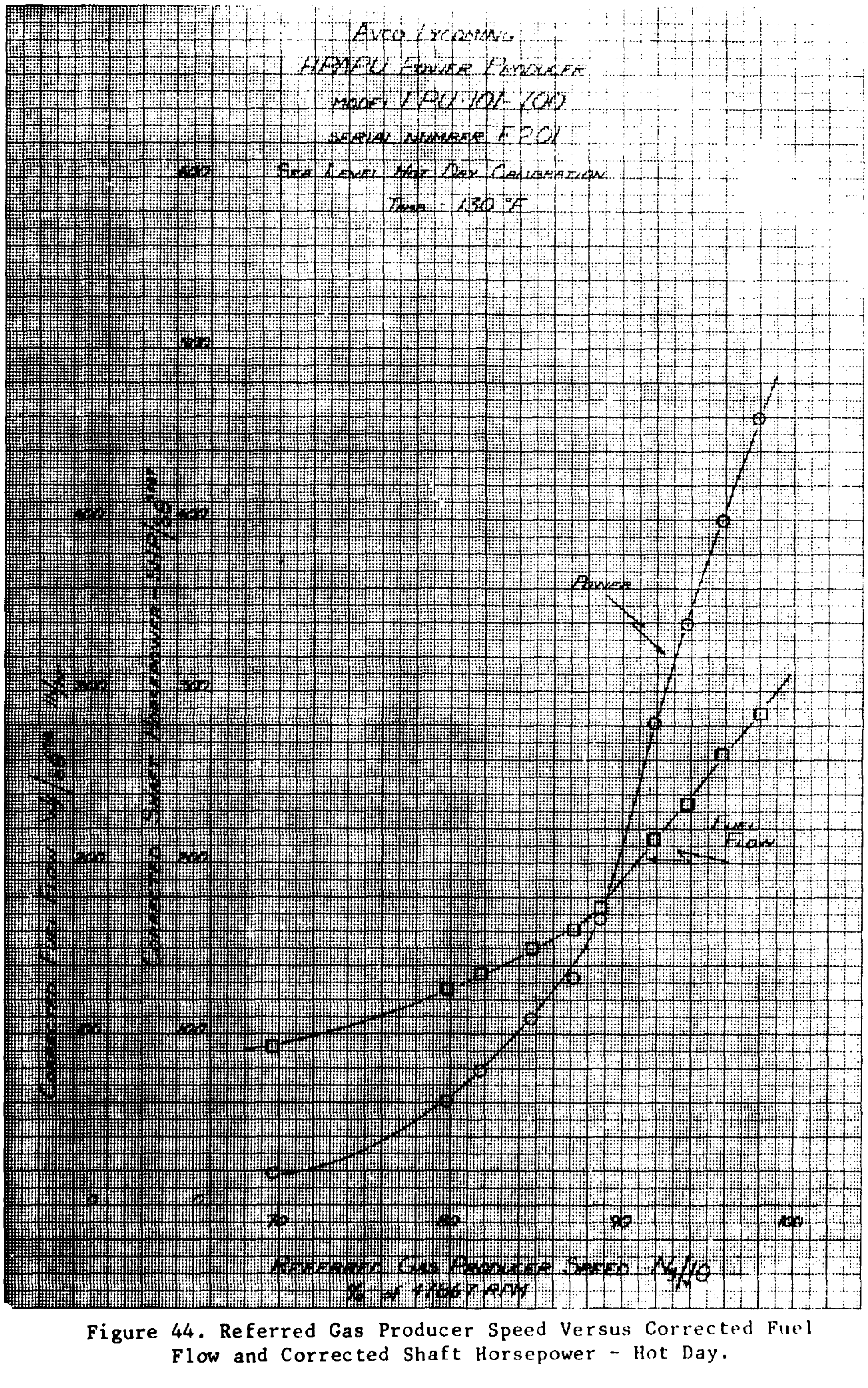


Figure 44. Referred Gas Producer Speed Versus Corrected Fuel Flow and Corrected Shaft Horsepower - Hot Day.

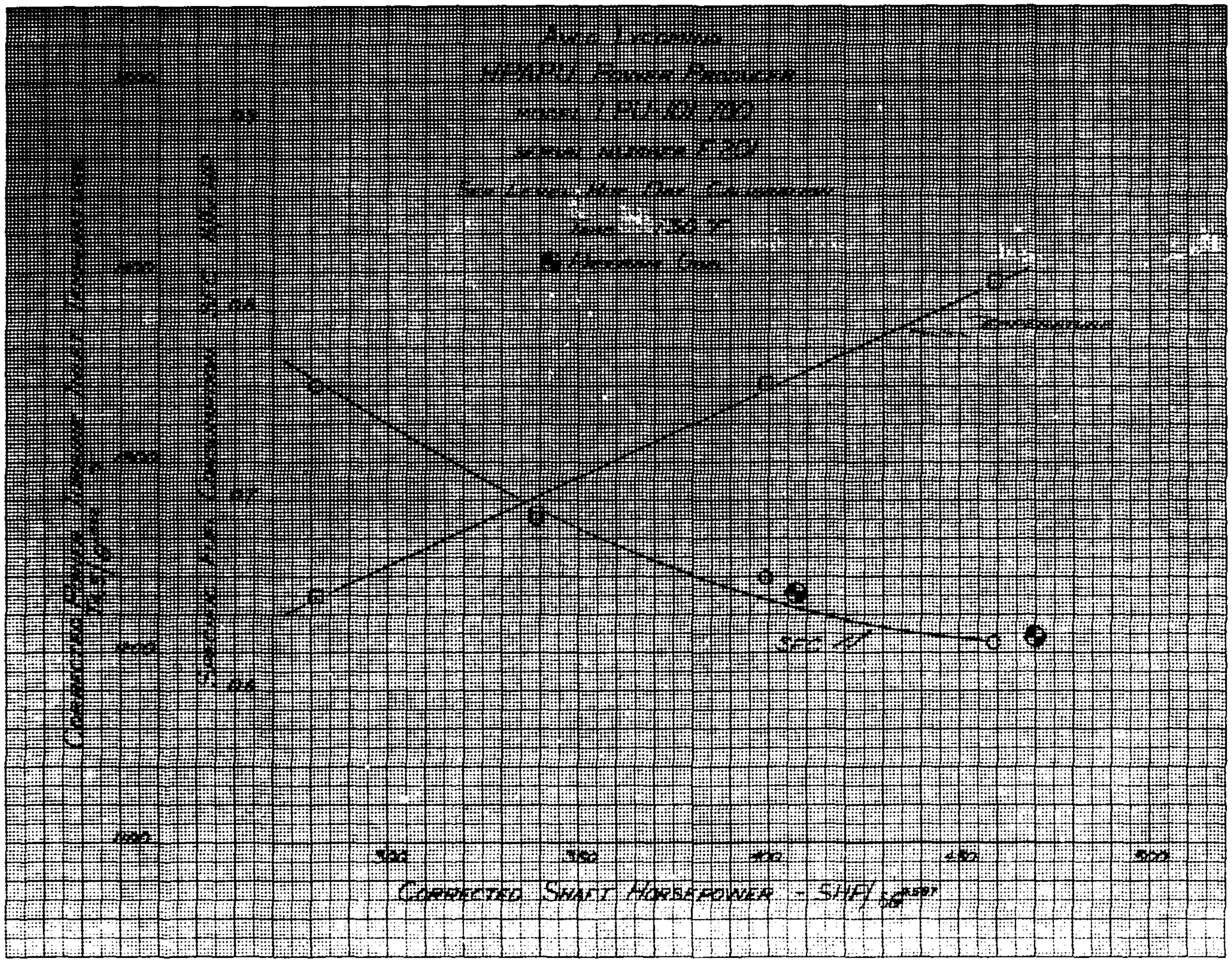


Figure 45. Corrected Shaft Horsepower Versus Corrected Power Turbine Inlet Temperature and Specific Fuel Consumption - Hot Day.

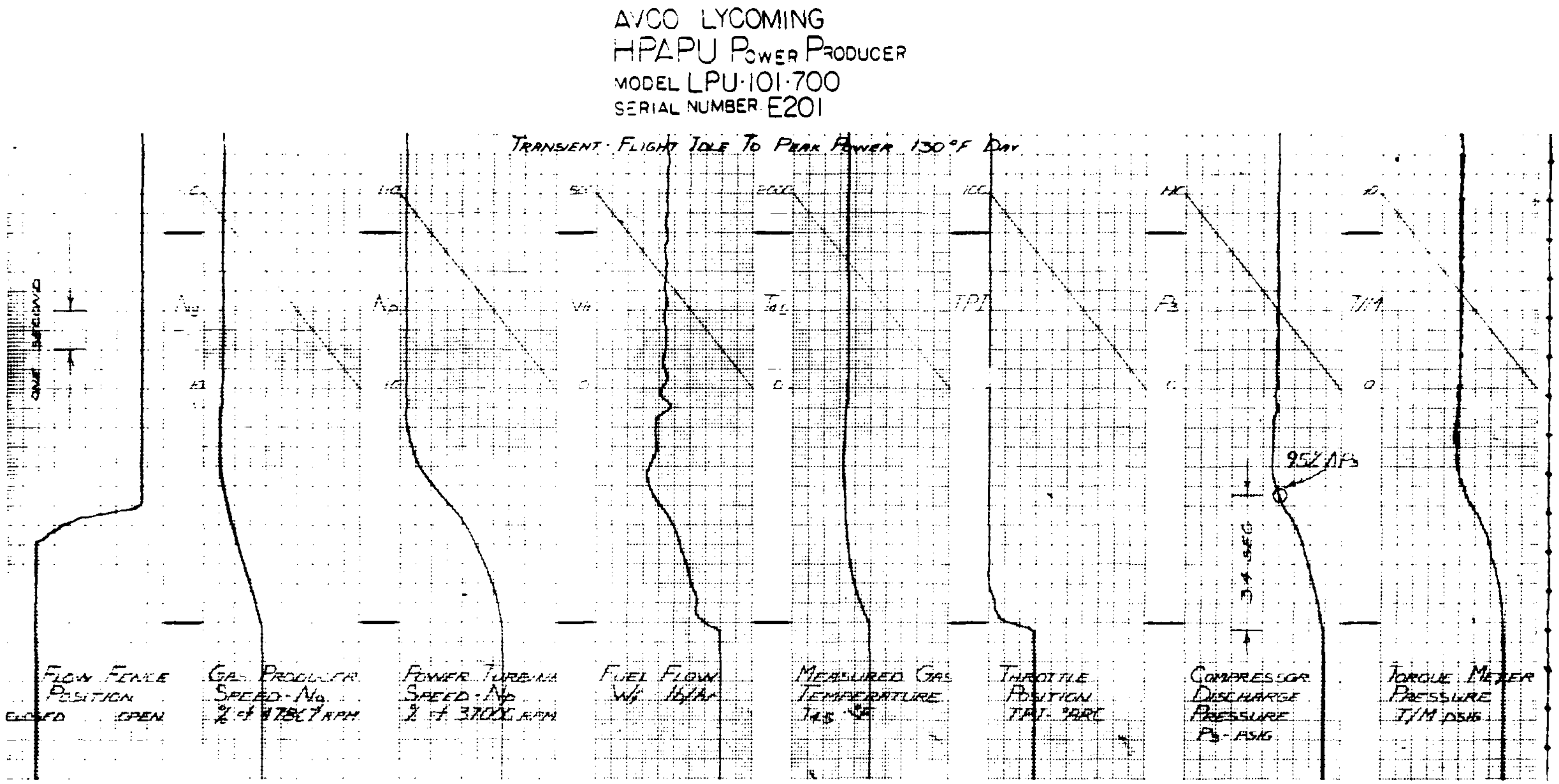


Figure 46. Transient Flight Idle to Peak Power - Hot Day.

During start number 30, a battery powered restart, the engine experienced an overtemperature condition of 1800°F (1650°F is normally considered the maximum allowable starting temperature). The start, conducted at 141°F inlet temperature, was not aborted but allowed to proceed until the engine achieved self-sustaining idle.

The fuel control was suspect and removed for bench evaluation. The start scheduling metering valve was updated to the latest design and the control returned to service. The original metering valve was a spring-loaded piston spill valve that would increase the starting fuel flow at a fixed control ΔP; the new design features a controllable orifice spill valve.

The results of the fuel control update are evident in the average measured gas temperature during starting. Prior to modification, the hot-day starting temperature were approximately 1400°F for initial starts and approximately 1640°F for restarts. These values were decreased approximately 200°F (1200° and 1400°F) following the fuel control update. See Table 10.

All starts conducted during the sea level hot-day demonstration, except for start number 30 previously discussed, were free from excessive measured gas temperature or objectionable compressor roughness. All starts were conducted well within the maximum allowable time of 60 seconds as defined in Military Specification MIL-P-8686 (ASG).

For this phase of testing, the minimum and maximum engine inlet air temperature demonstrated were 137° and 148°F, respectively, versus the required value of 130°F.

Cold Day (-65°F)

A performance calibration was conducted with an engine inlet air temperature of -65°F. Data obtained during this calibration were affected by severe ice accretion on the inlet air screen. The calibration was interrupted on several occasions to de-ice the test equipment screen. On return to high power, however, the problem reoccurred. The calibration was allowed to proceed in this interrupted stepwise fashion.

Results of the -65°F calibration are presented in Figures 47 and 48. The data were analyzed by assuming a total pressure at the engine inlet plane. This total pressure was derived from the actual logged inlet nozzle static pressure versus an assumed mass flow static pressure. The maximum correction was approximately 6 to 7 inches H_2O at full power. The data were further corroborated by a posttest sea level standard condition. This calibration was corrected by -65°F inlet temperature and is presented on Figures 47 and 48 as predicted data.

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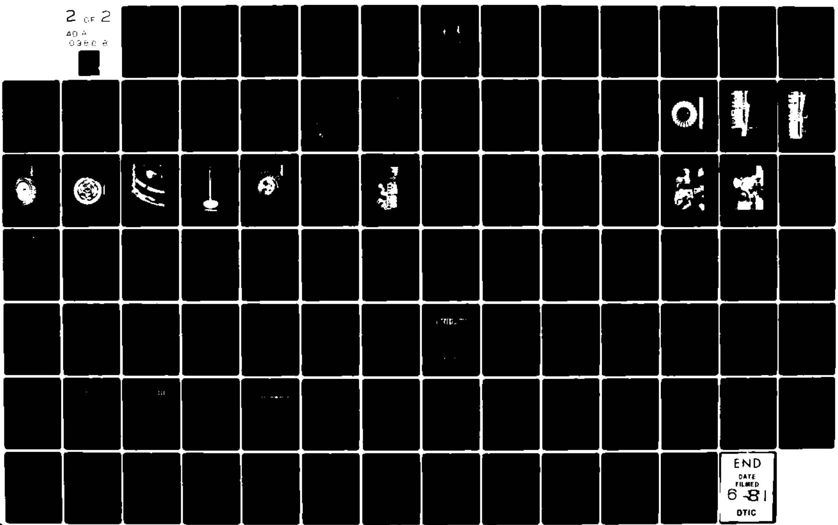

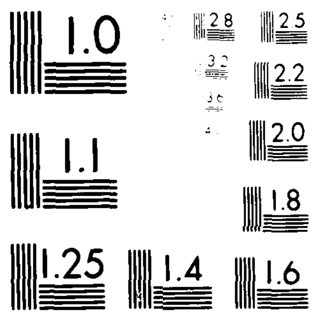

MICROCOPY RESOLUTION TEST CHART

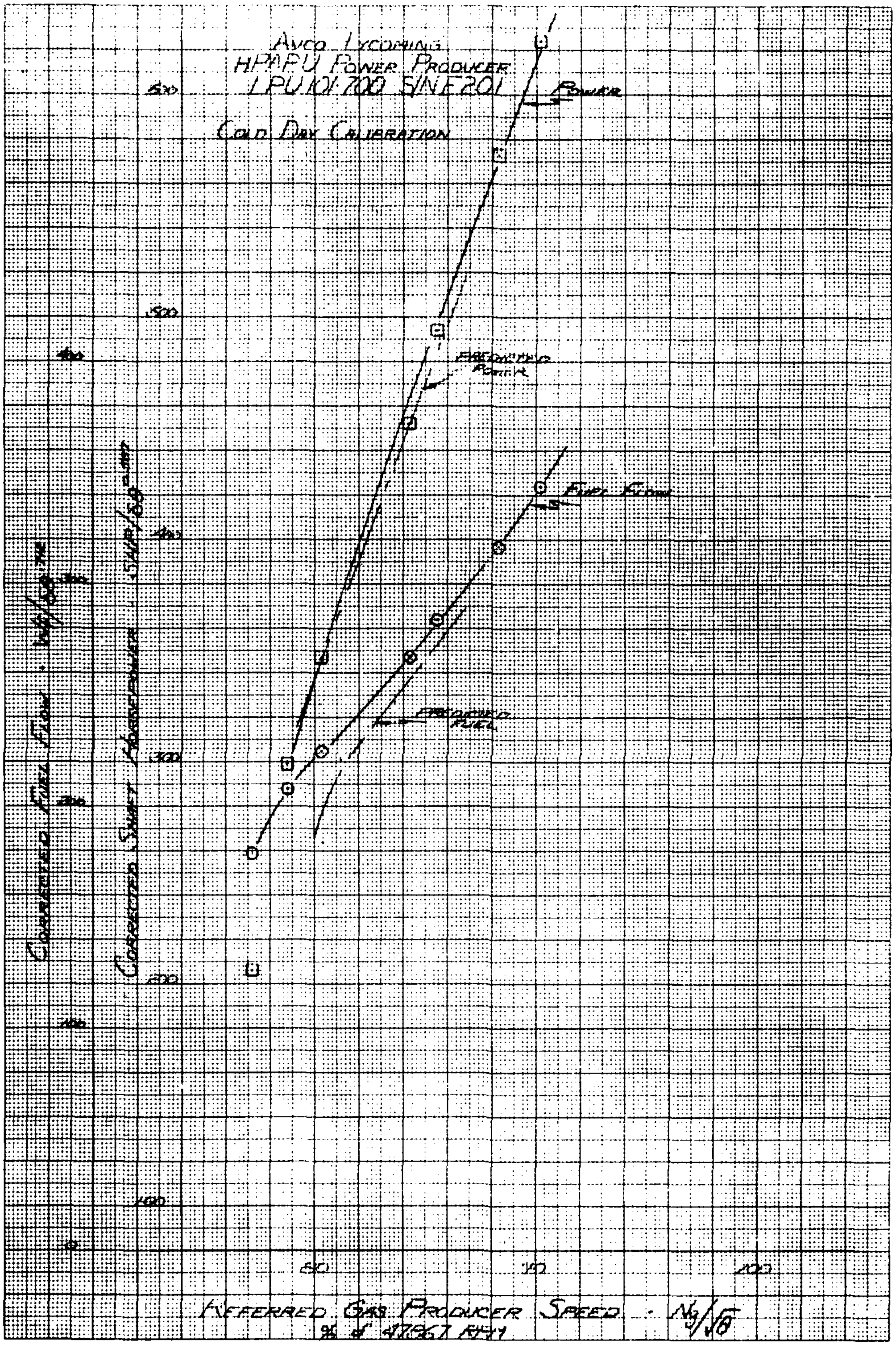

Figure 47. Referred Gas Producer Speed Versus Corrected Fuel Flow and Corrected Shaft Horsepower - Cold Day.

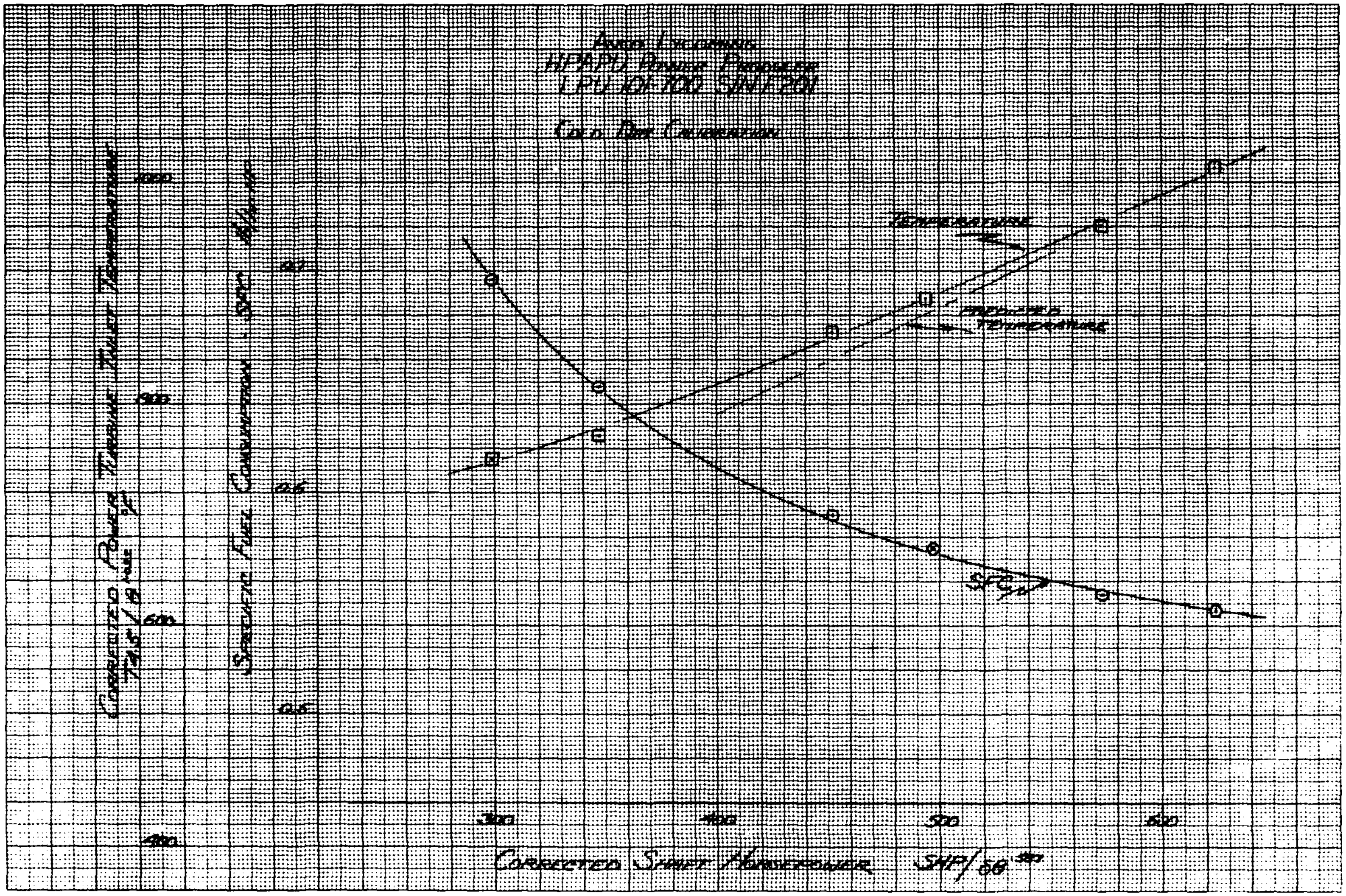

Figure 48. Corrected Shaft Horsepower Versus Corrected Power Turbine Inlet Temperature and Specific Fuel Consumption - Cold Day.

Predicted data and the data logged during the -65°F calibration exhibit excellent correlation on power versus gas producer speed basis. Measured as temperature correlated within 10°-20°F on a power basis. Measured fuel flow exhibited the largest degree of error but was within 5 percent of the predicted value.

Transient performance was determined by conducting power transients from ground and flight idle to peak power. The engine achieved 95 percent of the power change within 4.3 and 1.6 seconds, respectively. Again, the transients were free of any objectionable combustion roughness or compressor instability. Figure 49 is representative of these transients.

Cold starting demonstrations were conducted in the same manner as described earlier. To achieve sufficient mechanical starting power, a 250-ampere unit used during the conduct of the previous tests. Battery temperature was maintained at prevailing outside air temperature. Test results are given in Table 11.

TABLE 11. SEA LEVEL COLD-DAY STARTING DEMONSTRATION

Type of Start	Starter Type and Power Source	T Ambient (°F)	Max. MGT (°F)	Max. MGT (°F) Time to Idle (secs)
Initial	Electric Batt.	-67	680	75.4
Restart	Electric Batt.	-67	803	27.0
Initial	Electric Batt.	-67	830	56.4
Restart	Electric Batt.	-68	1201	30.9
Initial	Hydraulic	-71	650	65.8
Restart	Hydraulic	-70	694	23.7
Initial	Hydraulic	-70	798	57.8
Restart	Hydraulic	-68	782	24.3
Initial	Electric MG	-70	633	60.3
Restart	Electric MG	-69	1026	22.9
Initial	Electric MG	-70	589	76.0
Restart	Electric MG	-70	723	29.2

All starts conducted during the sea level cold-day demonstrations were free of excessive measured gas temperature or objectionable compressor roughness. All starts were conducted well within the maximum allowable time of 100 seconds as defined in Military Specification MIL-P-8686 (ASG).

All sea level testing was conducted with fuel and oil conforming to Military Specifications MIL-T-5624 (Grade JP-4) and MIL-L-7808, respectively. Samples of both the fuel and oil were subjected to laboratory analysis to confirm compliance with specifications.

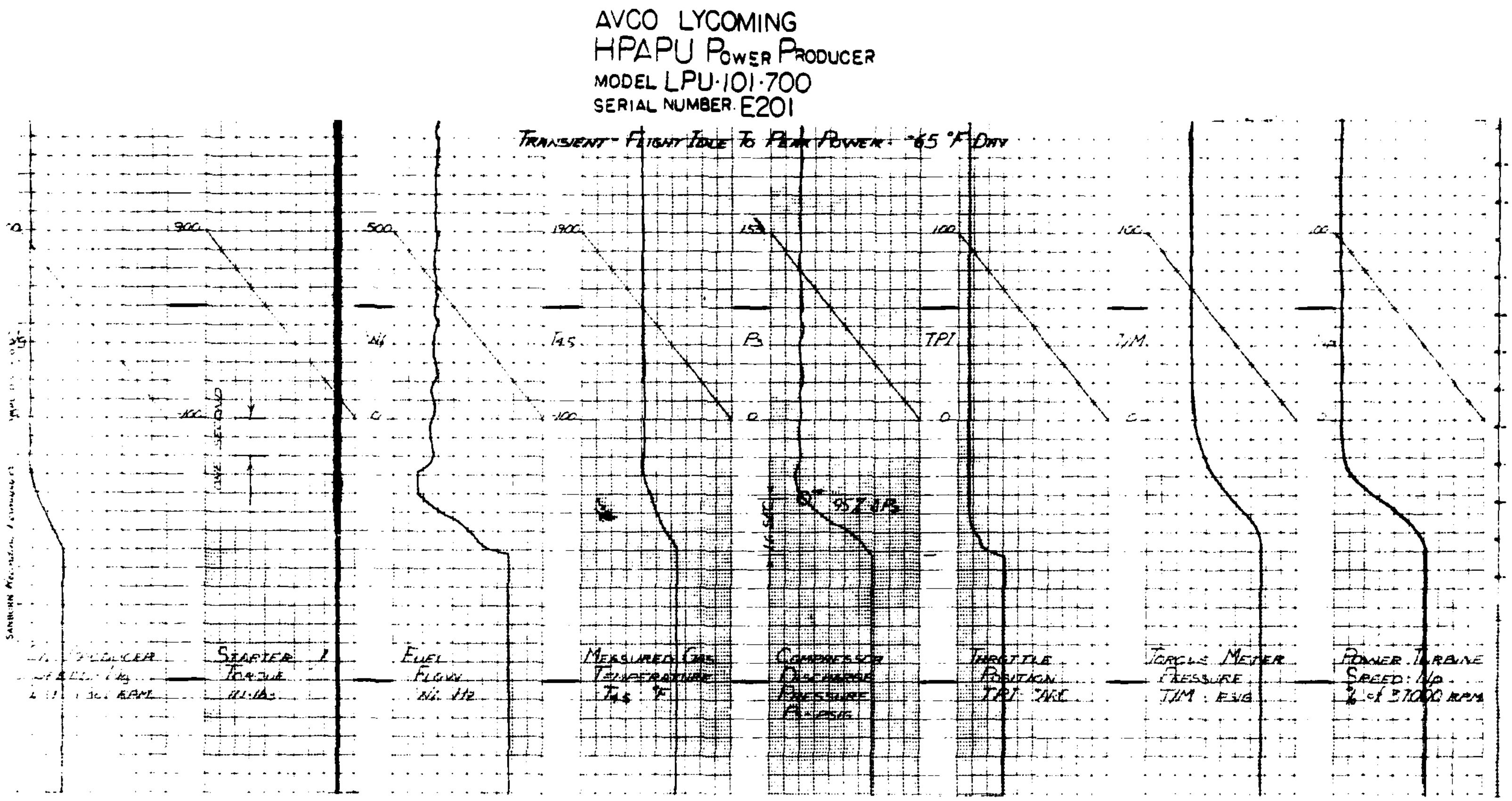

Figure 49. Transient - Flight Idle to Peak Power - Cold Day.

Mechanical performance throughout the sea level testing was normal. Engine case vibration levels were within acceptable limits throughout, as was oil consumption. The engine case vibration characteristic throughout the sea level testing is graphically depicted in Figure 50.

Altitude Start and Performance Calibrations

Results of the altitude starting demonstrations and performance calibrations conducted on HPAPU power producer are discussed below.

Predicted altitude performance of the HPAPU power producer was based on a referral of the pretest altitude performance calibrations. Due to slight variations in temperature and pressure during conduct of the altitude calibrations, normalization or referral of the data to standard day altitude conditions was necessary. Standard day conditions were those described in the U.S. Standard Atmosphere ASTIA Document 401813. The logged calibration data at 10, 20, and 25 thousand feet show good agreement with the predicted engine performance. These data are graphically depicted in Figures 51 through 53. Several data points were logged using alternate fuel and oil grades, Military Specifications MIL-T-5624 Grade JP-5 and MIL-L-23699, respectively. Results of this testing, also presented in Figures 51 through 53, indicate that the engine repeated the demonstrated altitude performance characteristics.

Pre- and post-altitude test performance calibration data show that the engine exhibited a speed shift during the course of the altitude test. The airflow pressure ratio characteristics of the compressor were found to be below the pretest baseline approximately 4 and 2 percent respectively. See Figures 54 and 55. This condition was attributed to compressor axial stage foreign object damage found at the conclusion of the test.

Facility limitations did not permit altitude power transients to be conducted. The engine inlet and chamber inlet valving, manually controlled throughout the test, could not be adjusted at the rate required to track response characteristic of the engine. Several attempts to conduct altitude power transients were negated by large fluctuations in engine inlet pressure.

Starting attempts were conducted at the three altitude conditions using either a motor-generator set or a 22-ampere hour nickel cadmium battery powering an Auxilec 250-amperes starter generator.

Checkout starts were accomplished with an Auxilec Model 524 150-ampere starter generator in conjunction with an unheated battery. Both 22- and 34-ampere hour batteries were investigated; however, neither one provided sufficient starter power. The combination of the 250-ampere Auxilec Model 8010B starter generator used in conjunction with a heated 22-ampere hour battery or a MG set provided adequate power to start.

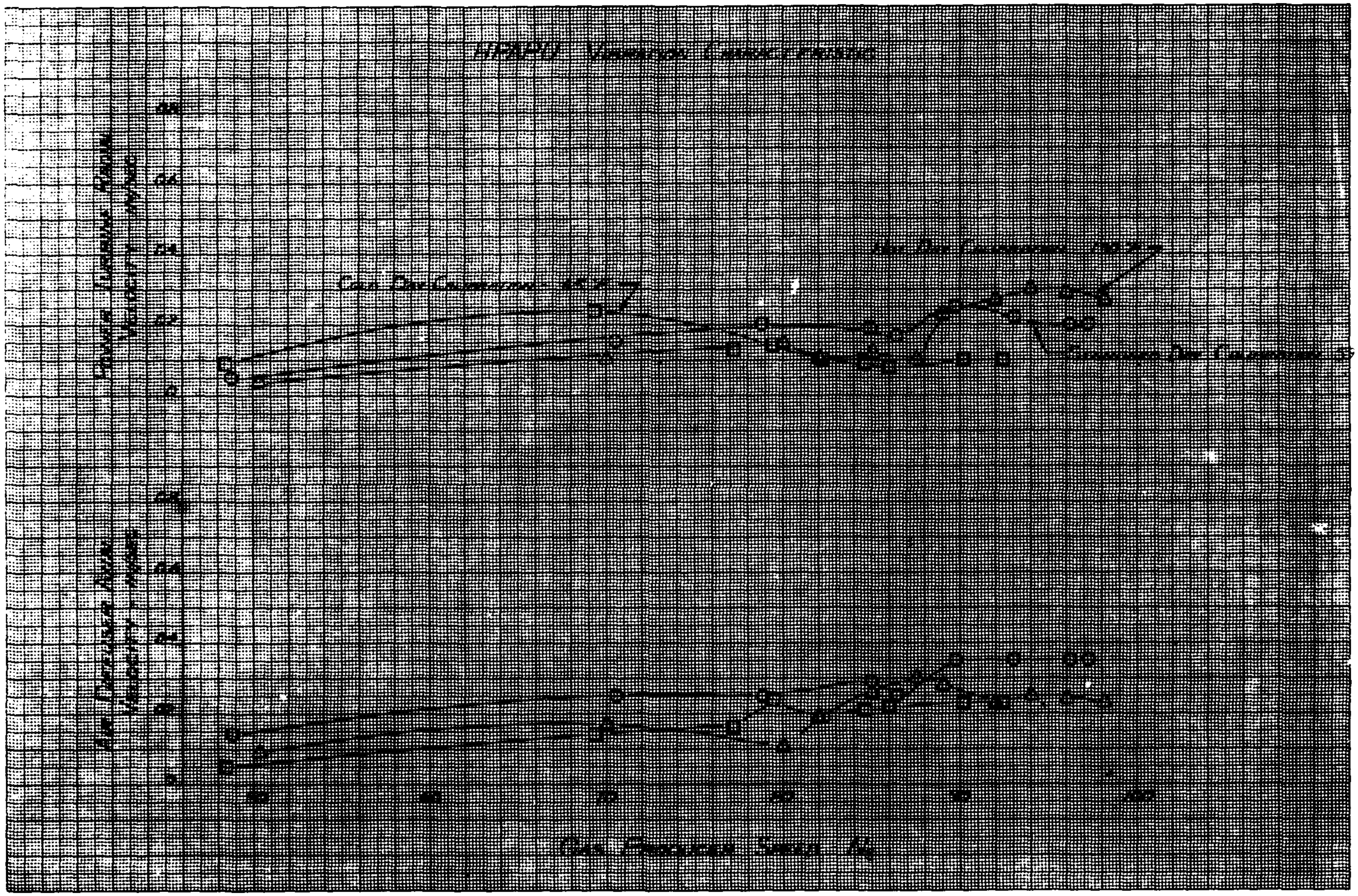

Figure 50. Hot, Cold, and Standard Day Vibration Characteristics.

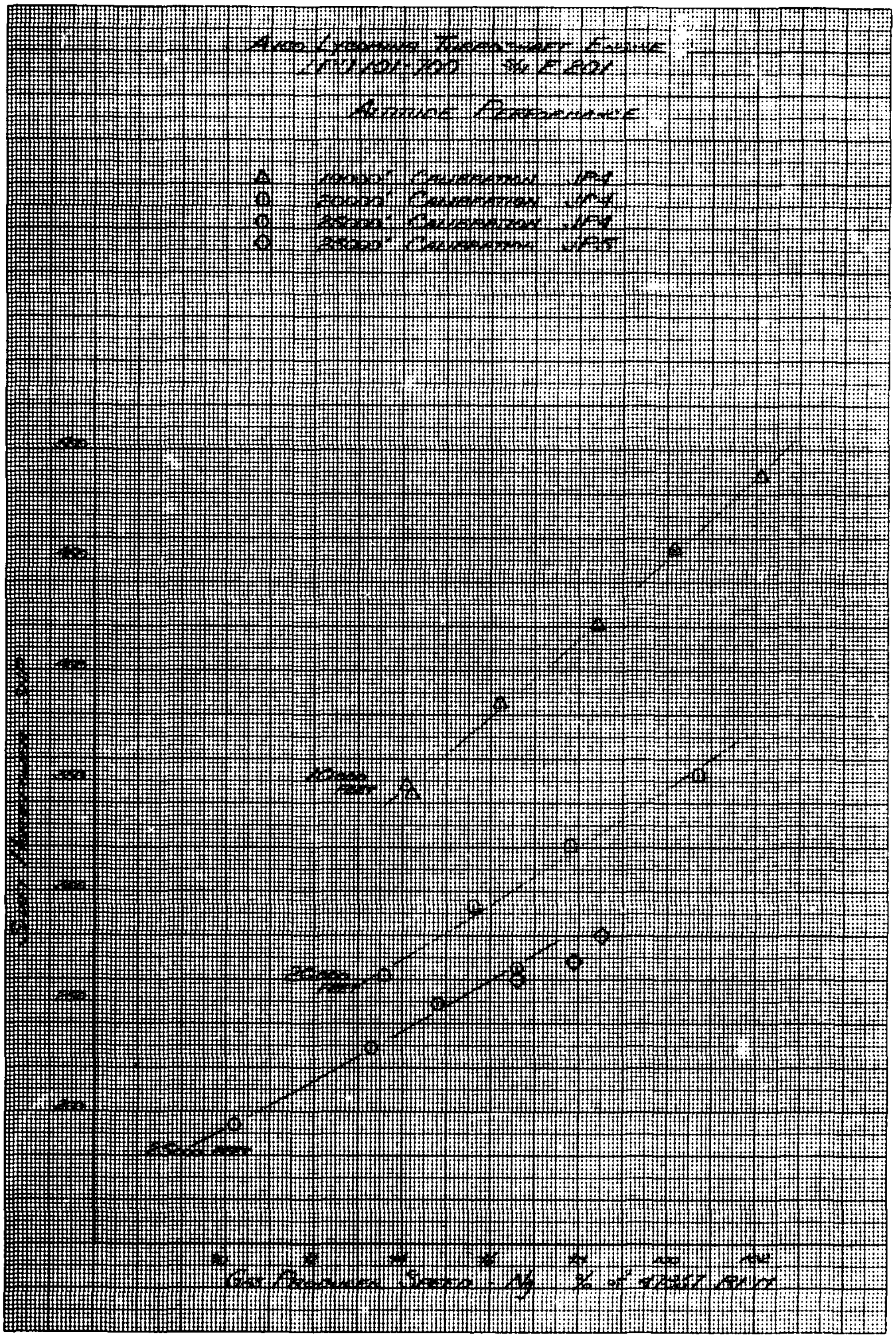

Figure 51. Gas Producer Speed Versus Shaft Horsepower at 10K, 20K, and 25K Feet.

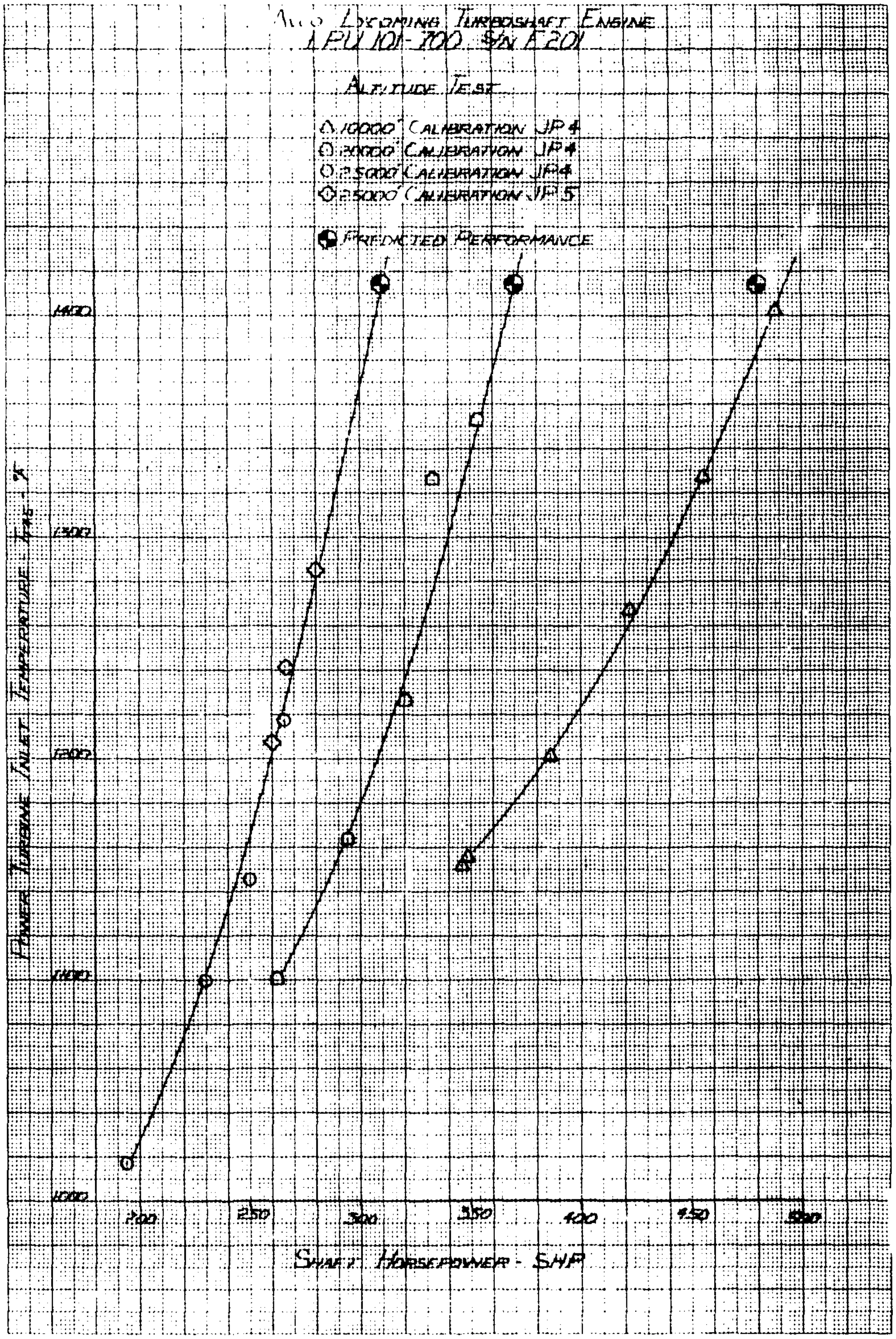

Figure 52. Shaft Horsepower Versus Power Turbine Inlet Temperature at 10K, 20K, and 25K Feet.

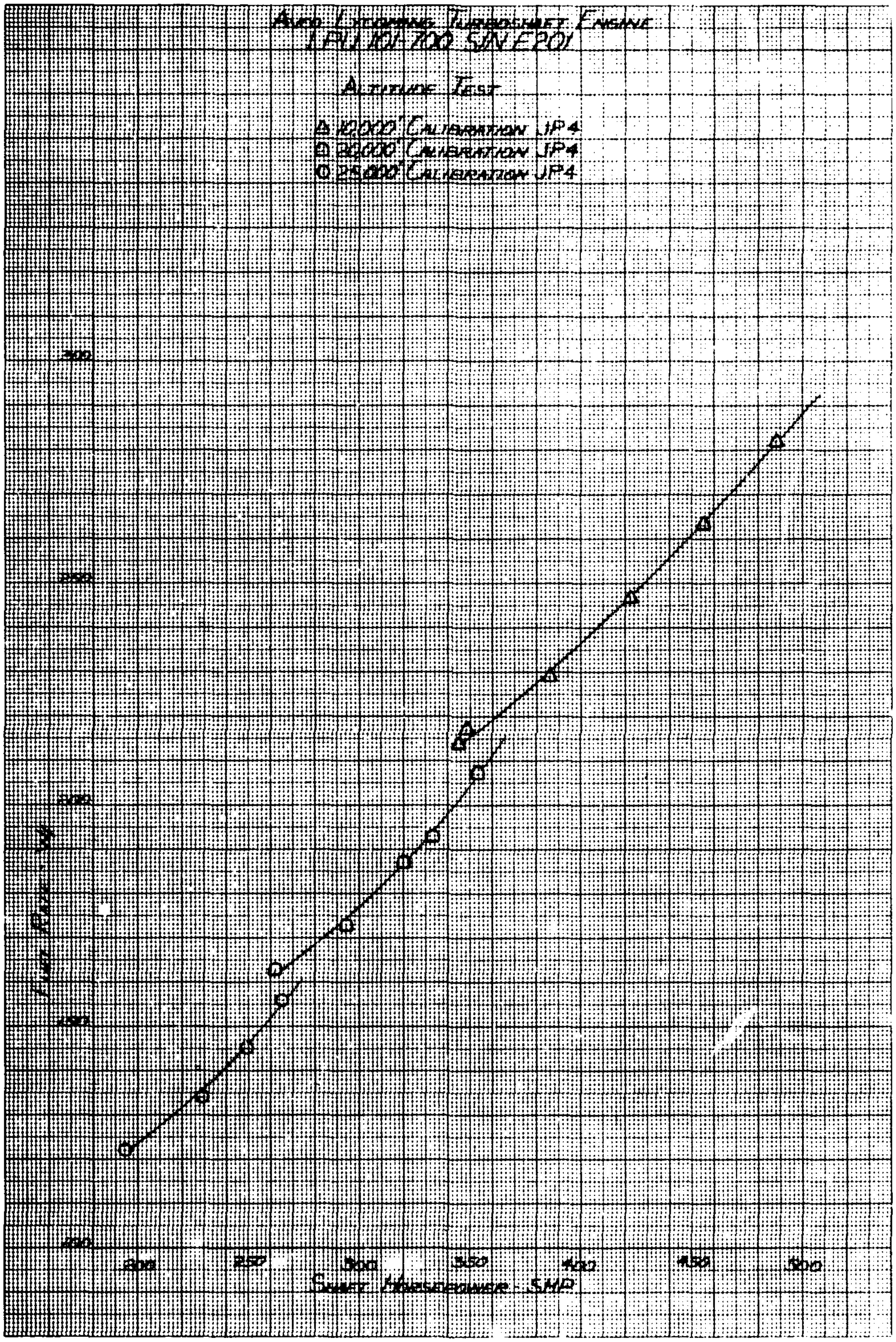

Figure 53. Shaft Horsepower Versus Fuel Rate at 10K, 20K, and 25K Feet.

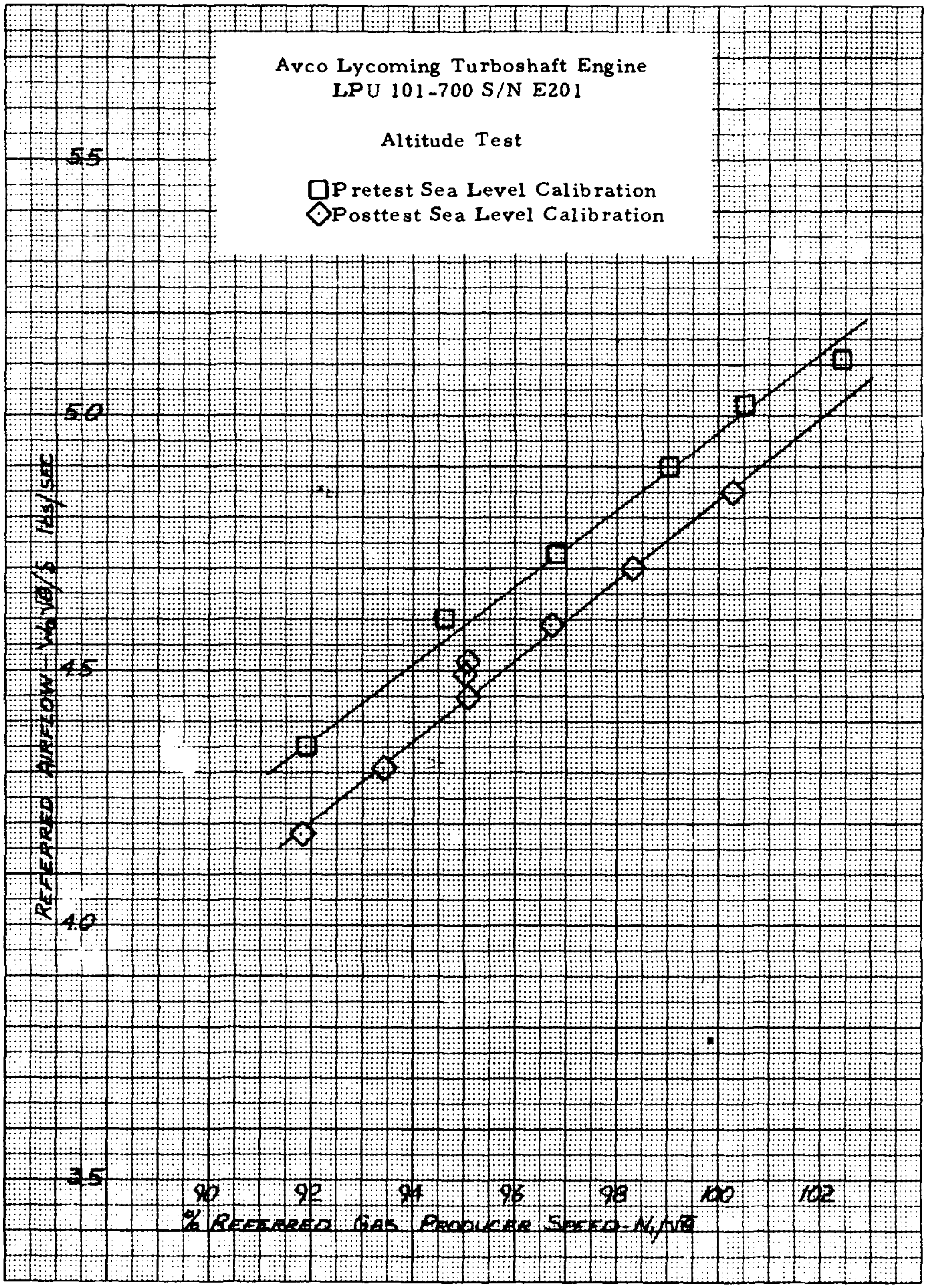

Figure 54. Referred Gas Producer Speed Versus Referred Airflow - Pre- and Post Altitude Test Calibrations.

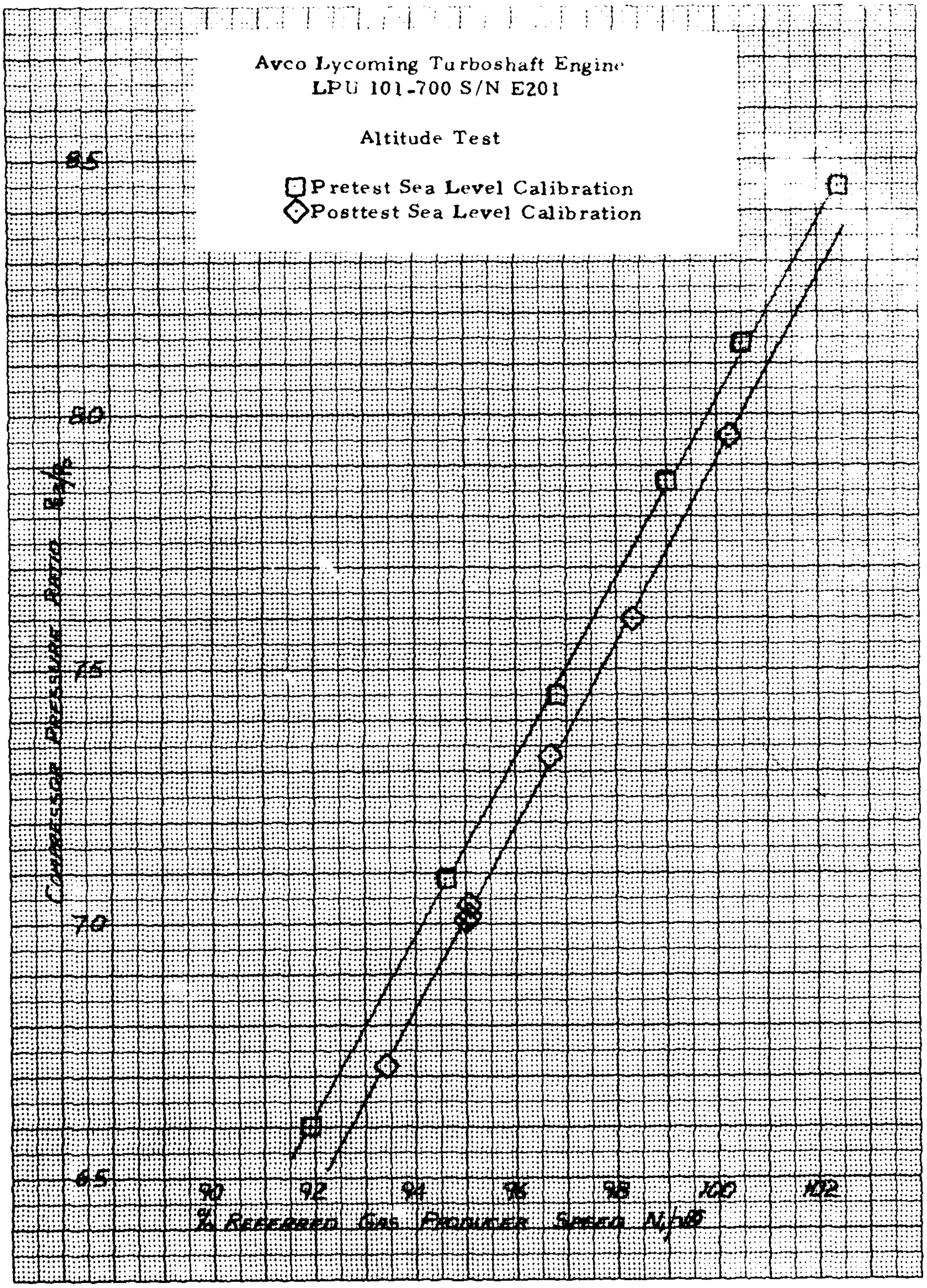

Figure 55. Referred Gas Producer Speed Versus Compressor Pressure Ratio - Pre- and Post Test Altitude Test Calibration.

The battery was subjected to the same altitude pressure as the engine but, with Air Force concurrence, was maintained at approximately room temperature by using electric heating elements.

Successful starts were accomplished to pressure altitudes of 20,000 feet using either of the starter power sources. These starts were conducted using a Bendix flowing pneumatic fuel control Model DP-S1 in conjunction with an Avco Lycoming start assist kit for the LTS 101 series engine. The Bendix control schedules start fuel as a function of an air pressure differential controlled by the throttle lever. The start assist kit for the LTS 101 consists of an electrical solenoid valve and piping to bypass the logic unit of the control and route fuel directly from the boost pump to the manifold. The assist fuel rate is controlled by a fixed diameter orifice.

The following starting procedure was used during the conduct of the 10,000 and 20,000-foot starts:

1. Engage starter, ignitors, and start assist

2. At 10 percent gas producer speed, advance throttle into start range

3. Upon ignition, disengage start assist

4. Following peak M.G.T., advance throttle to idle range.

This procedure is essentially the same method used on the LTS 101 throughout the general aviation industry. In addition, this procedure has successfully been incorporated in several military vehicular LTS 101 applications using automatic start logic.

During 20,000-foot sarts, it was often necessary to periodically engage and disengage the start assist in order to achieve a self-sustaining idle condition.

Oscillographic records of representative 10,000- and 20,000-foot starts are presented in Figures 56 and 57. Table 12 presents a synopsis of the test results.

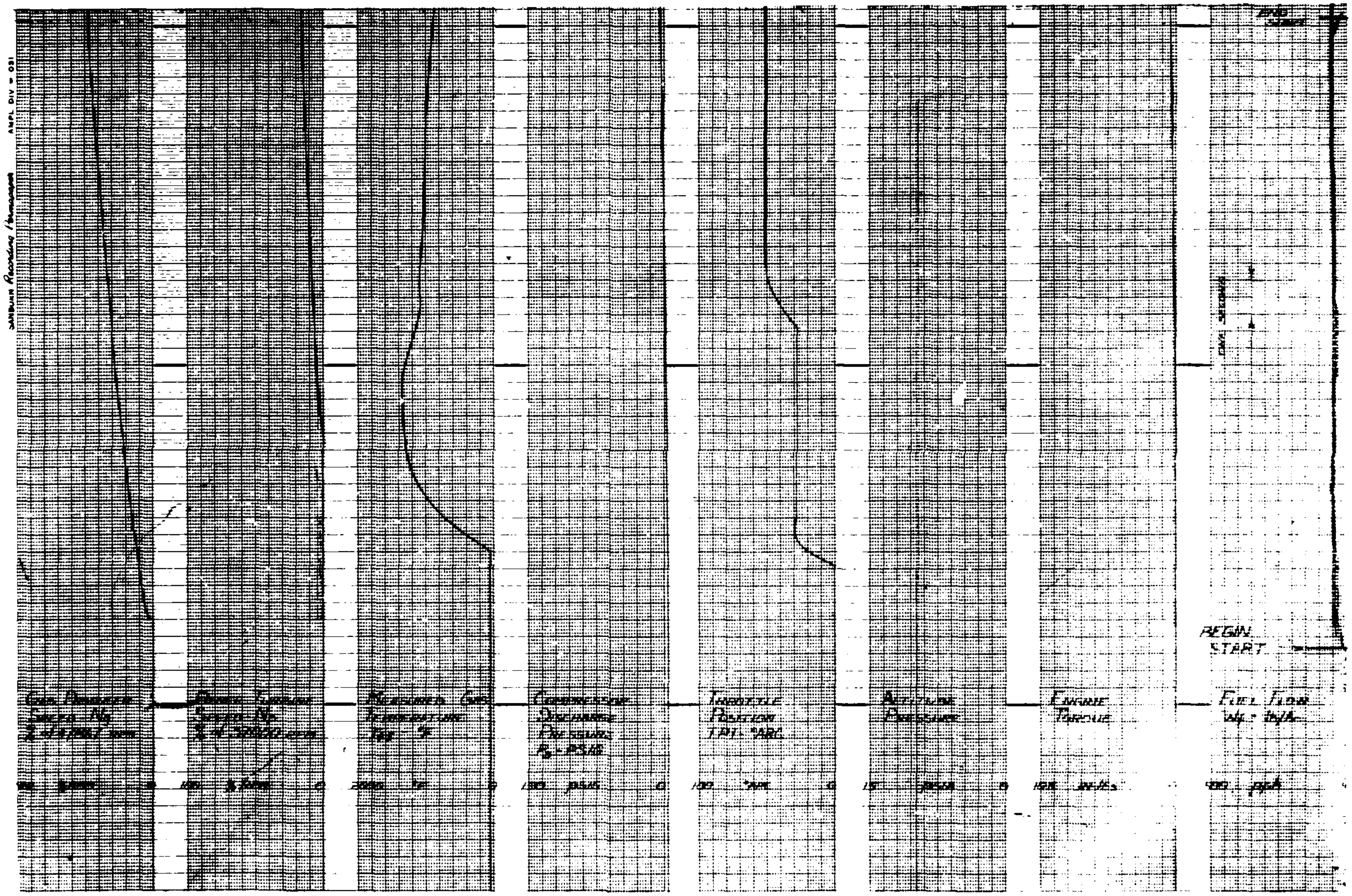

Figure 56. Battery Cold Start N[illegible] - 10,000 Feet.

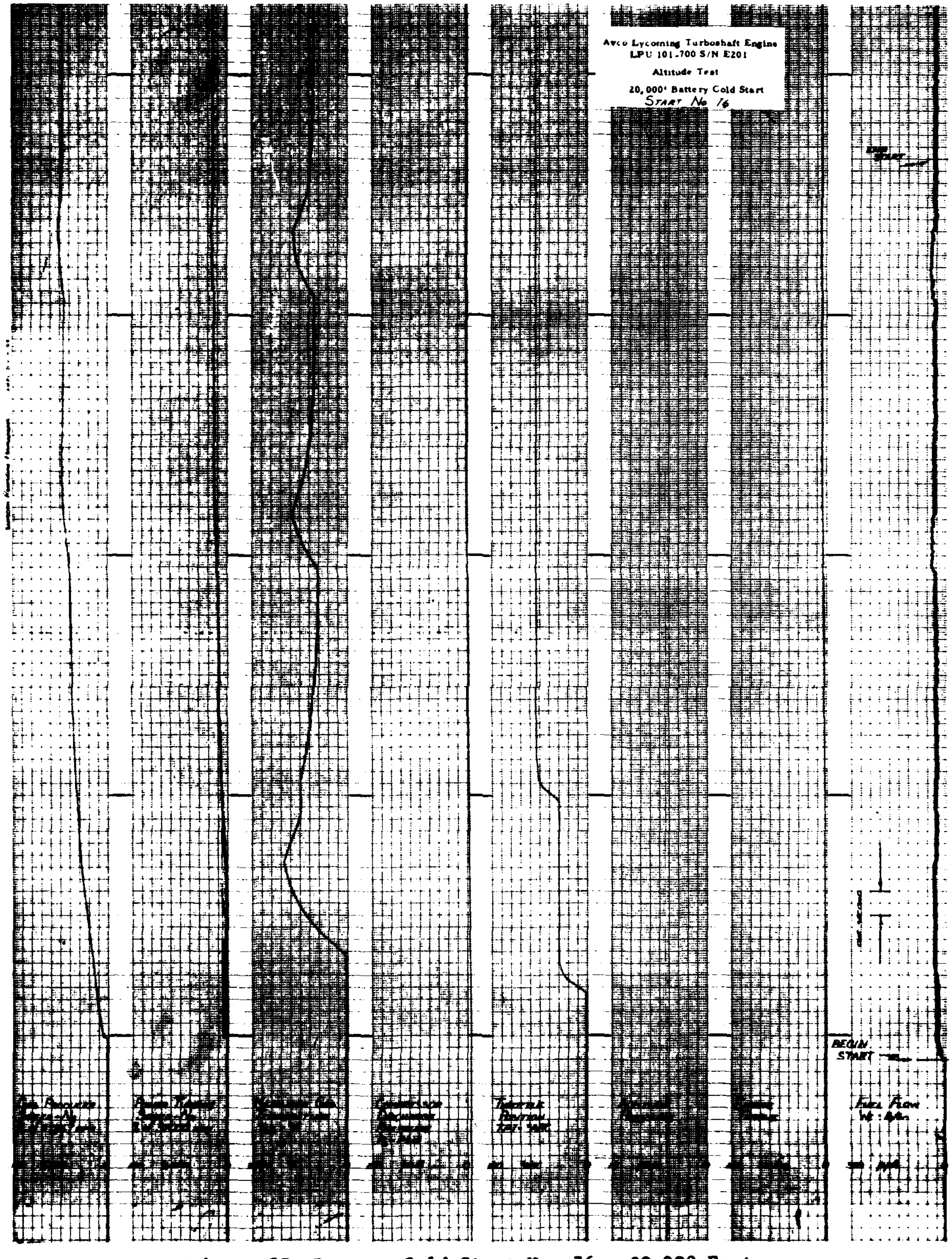

Figure 57. Battery Cold Start No. 76 - 20,000 Feet.

TABLE 12. HPAPU ALTITUDE STARTS

Type of Start	Altitude	Starter Power Source	T_{amb} (^oF)	T_{fuel} (^oF)	MGT Begin (^oF)	MGT Max (^oF)	Time to Idle (secs)
Cold	10K	Battery	21.3	-4.9	11.9	1222	18.5
Restart	10K	Battery	21.7	-0.9	166	1264	17.9
Cold	10K	Battery	25.9	-0.3	13.9	1306	19.1
Restart	10K	Battery	24.2	-3.5	160	1423	16.4
Cold	10K	MG	24.7	2.5	17.9	1183	17.9
Restart	10K	MG	26.0	-5.2	141	1261	17.1
Cold	10K	MG	28.9	1.7	21.4	1133	17.0
Restart	10K	MG	29.8	-6.9	115	976	20.4
Cold	20K	*Battery	19.7	-16.2	13.0	1340	98.3
Restart	20K	*Battery	20.7	-7.5	191	1443	30.4
Cold	20K	Battery	19.3	-17.6	2.7	1269	37.5
Restart	20K	Battery	20.9	-10.3	157	1530	23.6
Cold	20K	MG	14.8	-23.2	-4.3	1122	76.3
Restart	20K	MG	14.9	-17.3	175	1426	18.4
Cold	20K	MG	14.4	-30.0	-6.5	980	81.5
Restart	20K	MG	20.2	-24.5	131	1300	41.9

*Starts conducted with the 150 amp starter and an unheated 22 AH battery.

The cold starting demonstrations were preceded by a soak at the desired temperature for a period of at least two hours. This soaking period was conducted at essentially sea level pressure altitude. Just prior to the start attempt the chamber was brought to the desired pressure altitude. During this change in altitude both the engine inlet and chamber valving had to be closed to prevent windmilling of the compressor. With the low air mass flow under these conditions the inlet air temperature would begin to increase above the desired level. Included in the tabulated synopsis of test results are the prestart fuel and measured gas temperature levels to illustrate that the warming trend was most severe at the engine inlet air temperature sensor. The entire soaking period was conducted at the correct temperature and a test procedure was developed to limit the amount of time spent in changing the pressure condition within the chamber and hence limit the amount of warming of the inlet air temperature.

Starts at 25,000 feet with the Bendix flowing pneumatic fuel control were marginal with some attempts resulting in either a no light or an overtemperature condition. Figure 58 is an oscillographic record of a typical successful 25,000 foot restart.

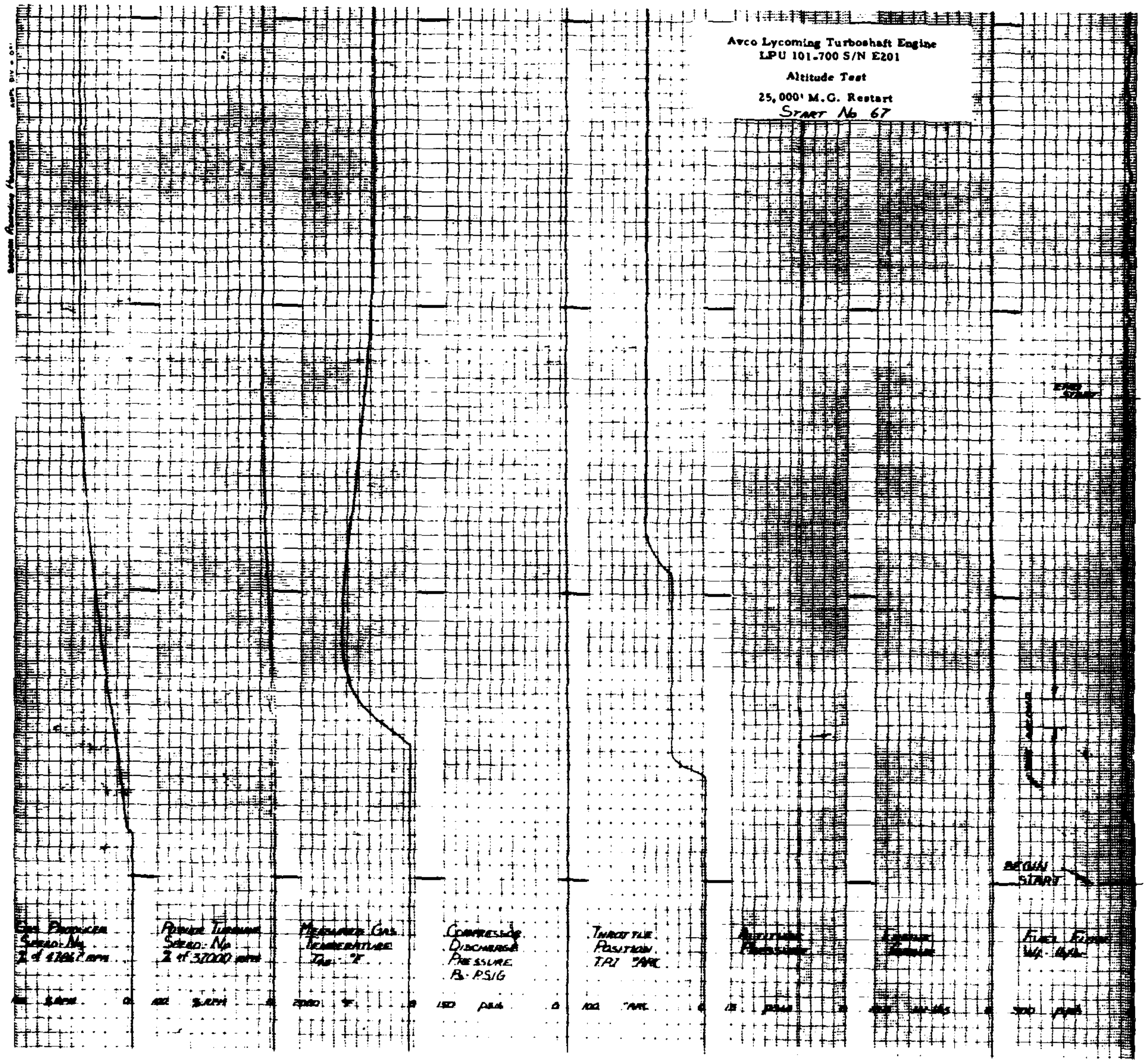

Figure 58. Motor Generator Restart No. 67 - 20,000 Feet.

High altitude starting characteristics were further investigated by using electronic fuel controls in lieu of the flowing pneumatic unit. Two electronic controls were investigated, namely:

Prototype Lucas Aerospace Electronic Fuel Control
Bendix Universal Test Control

The Lucas control is an aircraft unit using a constant time rate of compressor speed change ($\dot{N}$) logic during starting and transients. This control produced an improvement in high altitude starts over the flowing pneumatic control. Several anomalies precluded a complete demonstration with the Lucas prototype control. An erratic compressor speed signal (N_g) led to several operator terminated starts. In addition, minimum fuel flow produced starting directly to 90 percent gas producer speed (approximately 200 shp) because the steady-state fuel altitude bias feature was not enabled during testing. The starts to a power level above idle demonstrate the ability of the HPAPU power producer to start and accelerate to a usable power level without operational difficulty. The starting characteristics with the Lucas control are graphically depicted in Figures 59 and 60.

The Bendix Universal Test Control (UTC) is a laboratory control used to develop starting and acceleration fuel schedules. This control features manually controlled fuel scheduling. A successful high altitude start (Figure 61) was conducted with the Bendix UTC. This start was made with a ram pressure ratio of 1.23. It should be noted that starting characteristics at altitude were improved by ram. Table 13 summarizes the 25,000-foot starting results.

TABLE 13. HPAPU 25,000 FOOT STARTING RESULTS

Type of Start	Power Source	Altitude	T_{amb} (°F)	T_{fuel} (°F)	MGT Begin (°F)	MGT Max (°F)	Time to Idle (secs)
Restart - Bendix	MG	25K	25.4	-19.1	106	1250	17.0
Restart - Lucas Prototype Electronic	MG	25K	30	-10	19	1392	40.5*
Cold - Lucas Prototype Electronic	MG	25K	10	-28	1	1500	Aborted - no Ng speed signal
Cold - Bendix UTC	MG	25K	24.8	-46	18	1052	22.9

*Time to 90% Ng

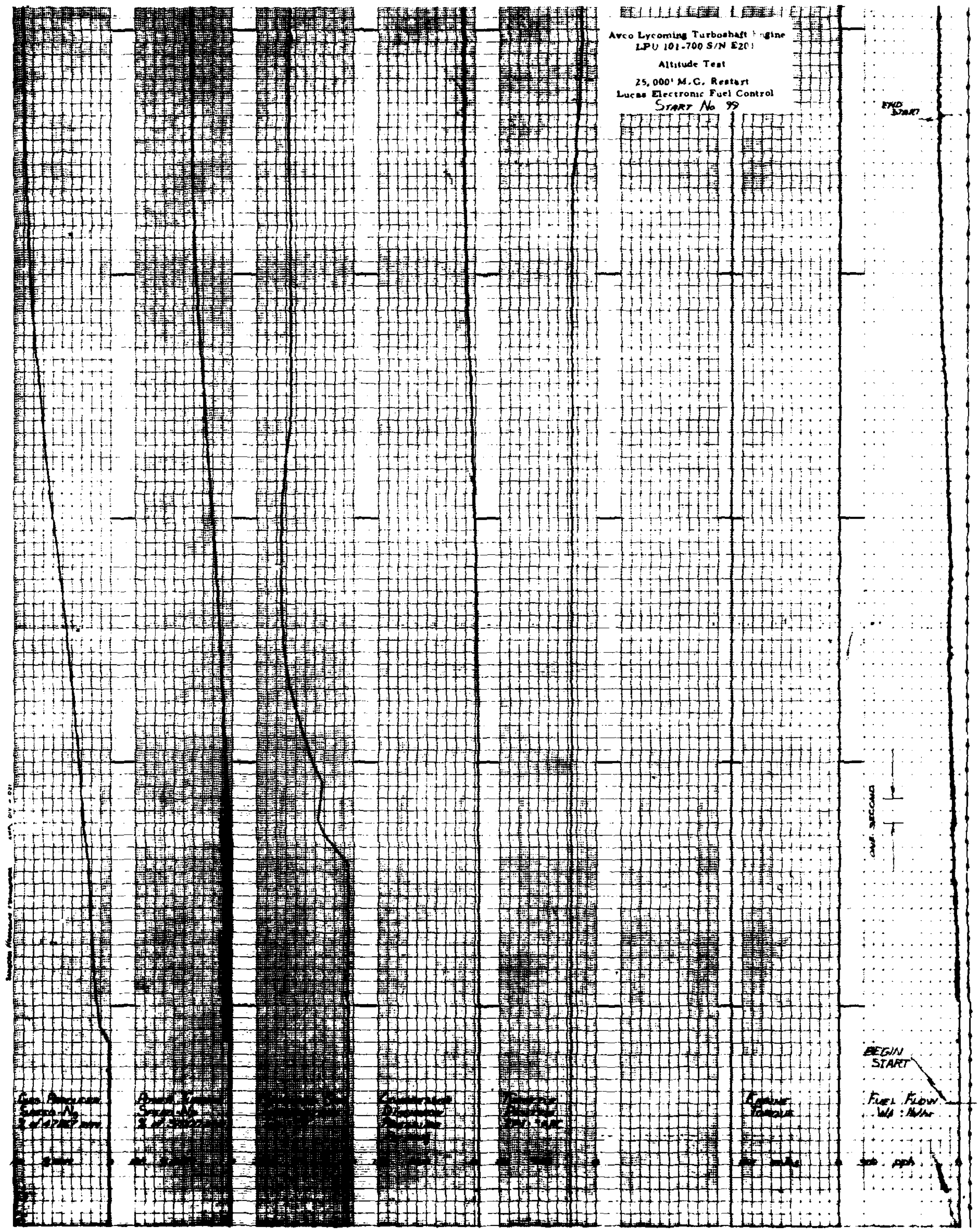

Figure 59. Motor Generator Restart No. 99 - 25,000 Feet - Lucas Electronic Fuel Control.

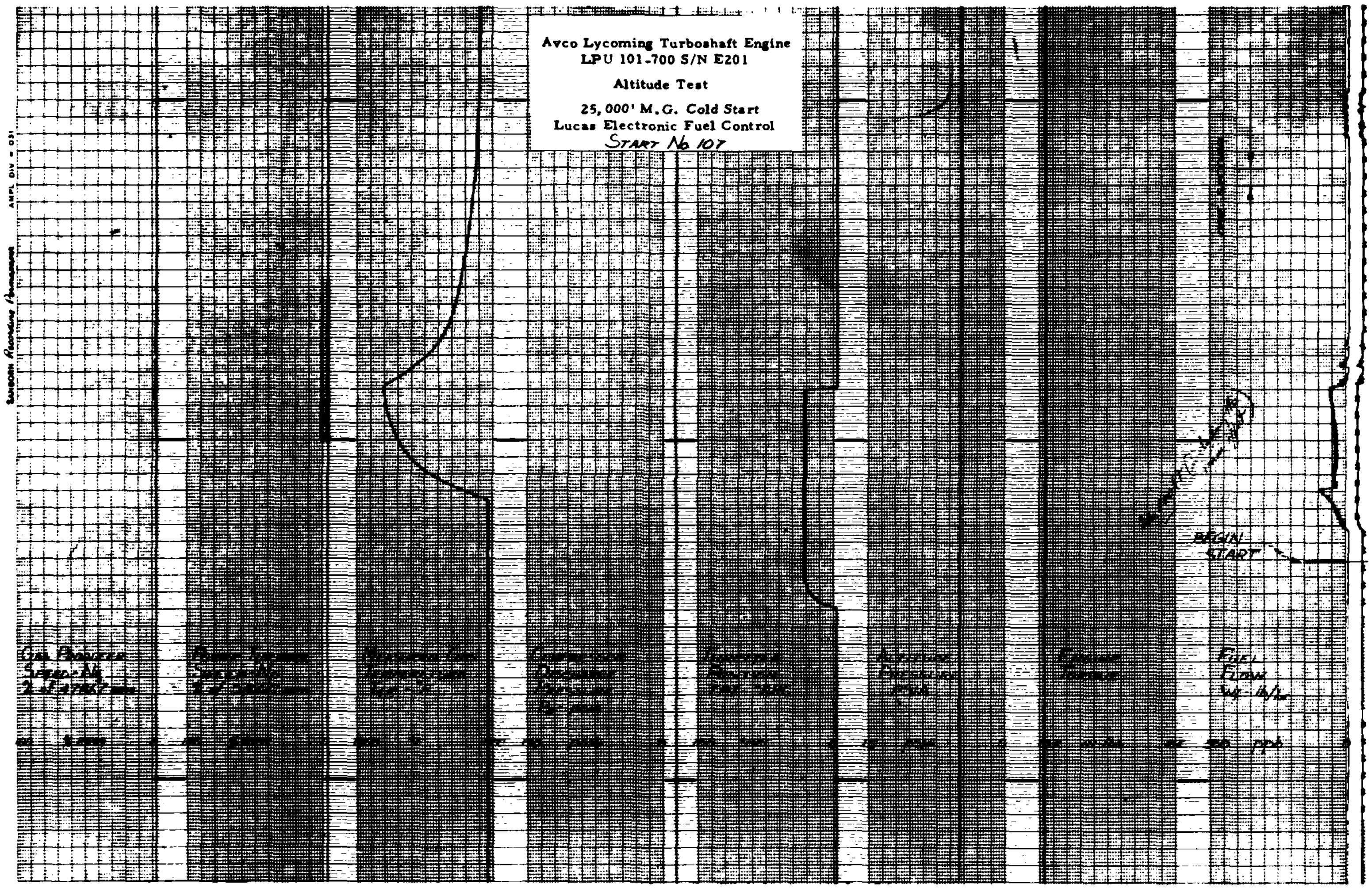

Figure 60. Motor Generator Cold Start No. 107 - 25,000 Feet - Lucas Electronic Control.

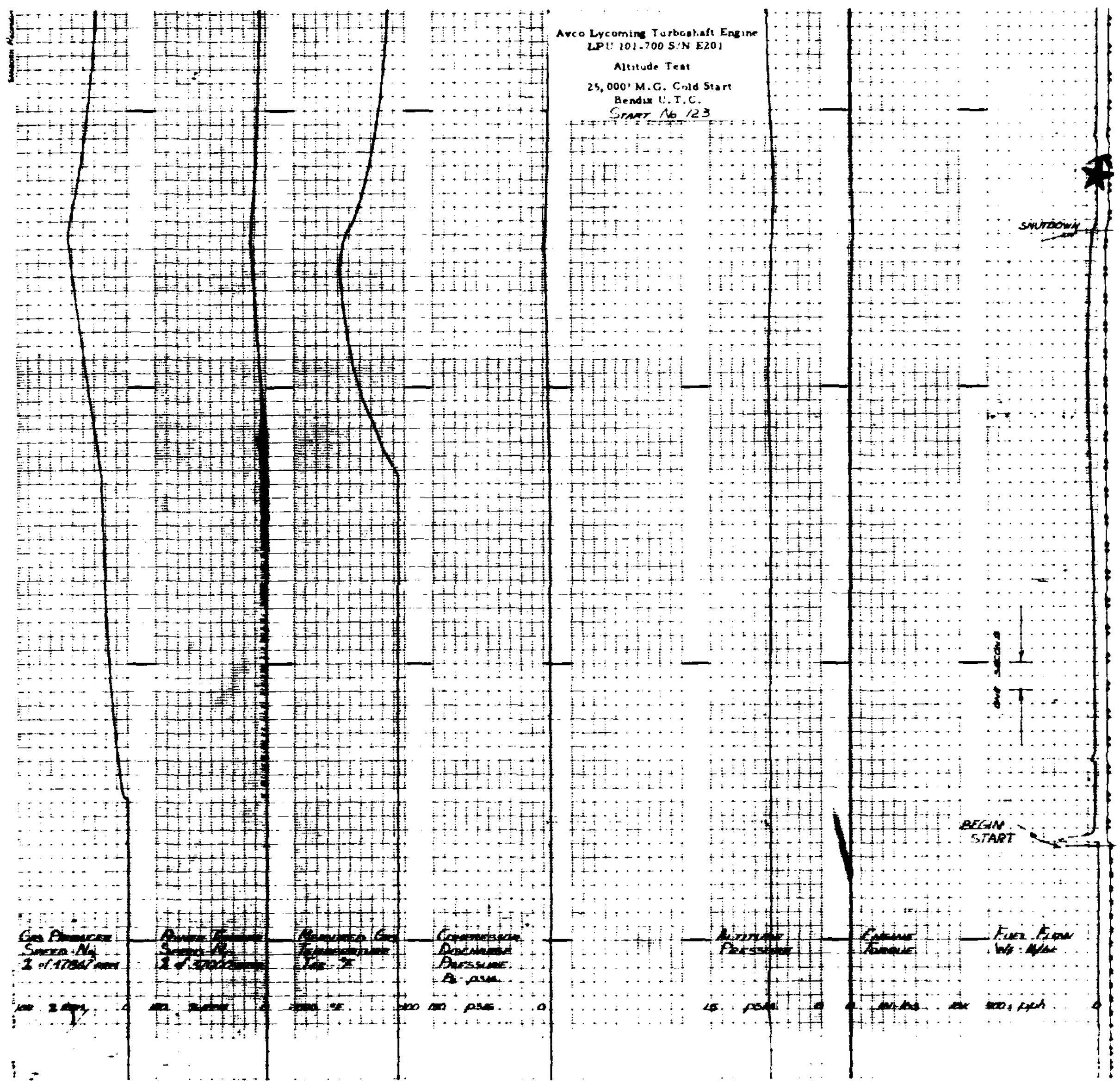

Figure 61. Motor Generator Cold Start No. 107 - 25,000 Feet - Lucas Electronic Control.

By use of the electronic fuel controls, a higher degree of starting success was achieved at 25,000 feet. The HPAPU power producer demonstrated the capability of high altitude starting, however, further refinement of the altitude start fuel scheduling is required.

Starting demonstrations were also conducted with MIL-T-5624 Grade JP-5 and MIL-L-23699 oil.

Successful starts were made at sea level to inlet air temperature of -36°F. Fuel was maintained at -24°F because of some slight water contamination. Upon completion of the start it was necessary to leave the enrichment system partially enabled for approximately seven minutes in order to maintain throttle response.

The maximum altitude investigated with the alternate fuel and oil combination was 15,000 feet. The DPS-1 Bendix flowing pneumatic control was used exclusively throughout this test phase with a modified fuel enrichment system. A successful start was conducted, however, throttle and enrichment system manipulation was required to prevent overtemperatures and to attain idle.

Table 14 summarizes the alternate fuel and oil investigation results.

TABLE 14. HPAPU ALTERNATE FUEL AND OIL STARTING RESULTS

Type of Start	Power Source	Altitude	T_{amb} (°F)	T_{fuel} (°F)	MGT Begin (°F)	MGT Max (°F)	Time to Idle (secs)
Start - JP-5 Bendix DP-S1	Batt	15K	41.1	-6.3	34	1389	54.8
Cold - JP-5 Bendix DP-S1	Batt	S.L.	-36	-24.0	-34.4	630	43.4
Restart - JP-5 Bendix DP-S1	MG	S.L.	-37.3	-3.5	93	1084	30.7

Engine mechanical performance was normal throughout the conduct of the altitude test. A total of 42.03 hours of engine operation were accrued during the altitude test. Included in this time are a total of 19.23 hours of operating at altitudes described below:

9.83 hours at 10,000 ft
5.40 hours at 20,000 ft
4.00 hours at 25,000 ft

Engine case vibration levels remained virtually unchanged throughout the altitude test and below the normal maximum allowable level of 0.8 in/sec average velocity. The compressor damage found during later inspection did not significantly increase the vibration levels.

The oil system used during the conduct of the altitude test typified that of an aircraft system and consisted of a reservoir, heat exchanger, and engine driven blower. No operational problems occurred during the conduct of the test and the oil consumption was negligible.

Inspection

Two hardware inspections were conducted during the conduct of the HPAPU environmental testing. The first inspection was conducted at the conclusion of the peak power, sea level hot and standard day, starting and performance demonstrations. This inspection was limited in scope and was conducted by Lycoming Engineering and Quality and Air Force Representatives. No major discrepancies were noted during this inspection. No deleterious effects of the high temperature start were noted. All of the engine hardware was suitable for continued use, however, the gas producer blading was replaced. This replacement was to update the engine to the Bill of Material parts list and not a result of blade distress. The original blading of C101 material was replaced with C103 to enhance life characteristics.

A crack was noted in the rear bearing support housing (P/N 4-141-160-02) in the outer gas path wall adjacent to the 6-o'clock strut. This crack was not considered of significant proportion to warrant replacement of the housing.

The second hardware inspection was conducted at the conclusion of the altitude testing. This inspection was in greater detail than the previous inspection and included visual, dimensional, fluorescent-penetrant, and magnetic-particle crack detection techniques.

The majority of the hardware was found to be in good to excellent condition and suitable for continued operation. The following parts had notable inspection findings:

Axial Compressor Rotor, P/N 4-101-006-21

Visual inspection revealed that the rotor had foreign object damage at the leading edge tips. Although the damage appeared severe it did not adversely affect the engine performance or vibration levels. The component was beyond repair limits and was replaced. See Figure No. 62.

Compressor Vane Assembly, P/N 4-101-010-08

Visual inspection revealed that one vane was dented and another nicked at the leading edges. This damage, considered to be a result of the ingestion of the foreign object, is repairable.

Air Diffuser and Cover,m P/N 4-101-090-08 and P/N 4-101-170-08

The air diffuser vanes showed slight cracking at tht leading edge of three vanes and damage from the ingestion of the foreign object. The vane cracking appears to be a result of non-uniform vane clamping by the diffuser cover and normally does not propagate. The diffuser is considered acceptable for further use, however, spare components will be substituted upon reassembly. See Figure Nos. 63 and 64.

Gas Producer Rotor, P/N 4-111-030-03

The gas producer rotor was found to be generally in very good condition at test completion. The rotor is suitable for continued use following the replacement of the one blade, which revealed a casting defect upon fluorescent penetrant inspection. See Figure No. 65.

Combustor Housing, P/N 4-141-160-02

The overall condition of the combustor housing was good to excellent. The crack detected in the initial inspection did not propagate. The component is suitable for further use. See Figures 66 and 67.

Power Turbine Rotor Assembly, P/N 4-141-070-11

The power turbine rotor assembly exhibited light scoring at the forward bearing journal and the speed pickup plug. These marks are normally a result of disassembly and assembly of the power producer to the reduction gearbox. Fluorescent penetrant inspection also revealed minor surface inclusions in the rotor. These inclusions were blend repaired and the turbine is suitable for further use. See Figures Nos. 68 and 69.

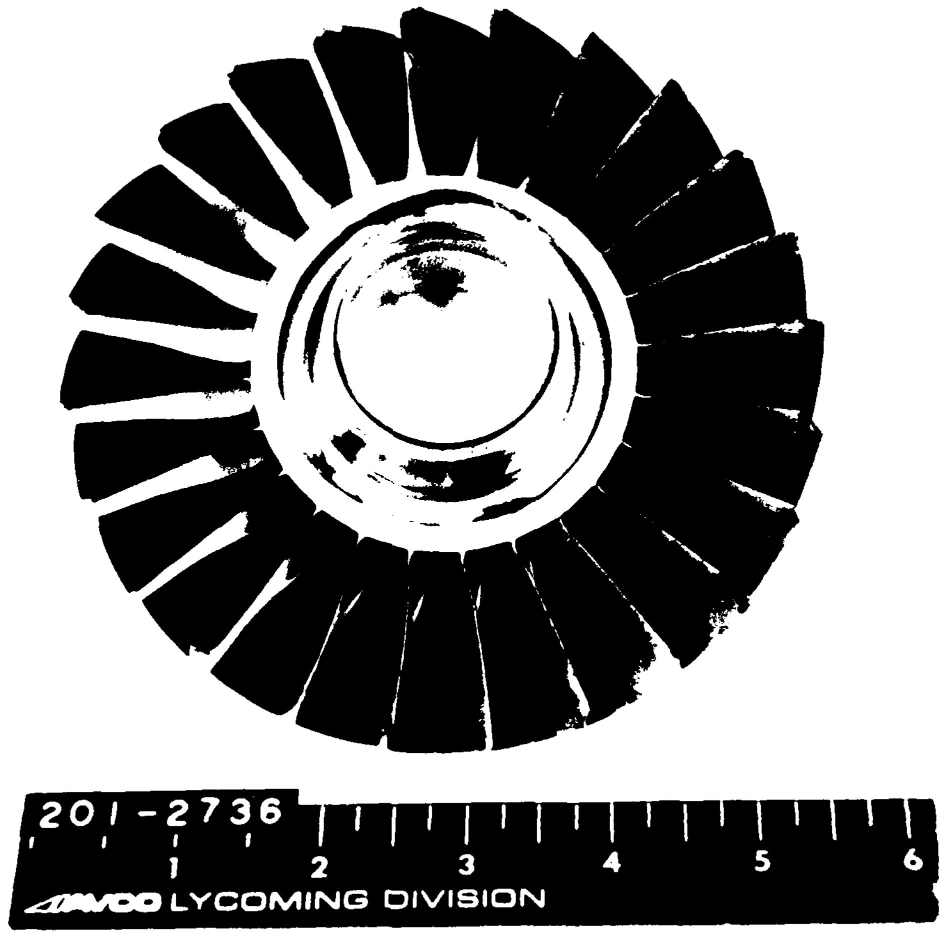

Figure 62. Axial Compressor Rotor with Foreign Object Damage (F.O.D.).

Figure 63. Diffuser Blade (Arrow Shows Leading Edge Crack).

Figure 64. Diffuser Blade (Arrow Shows Foreign Object Damage (F.O.D.)).

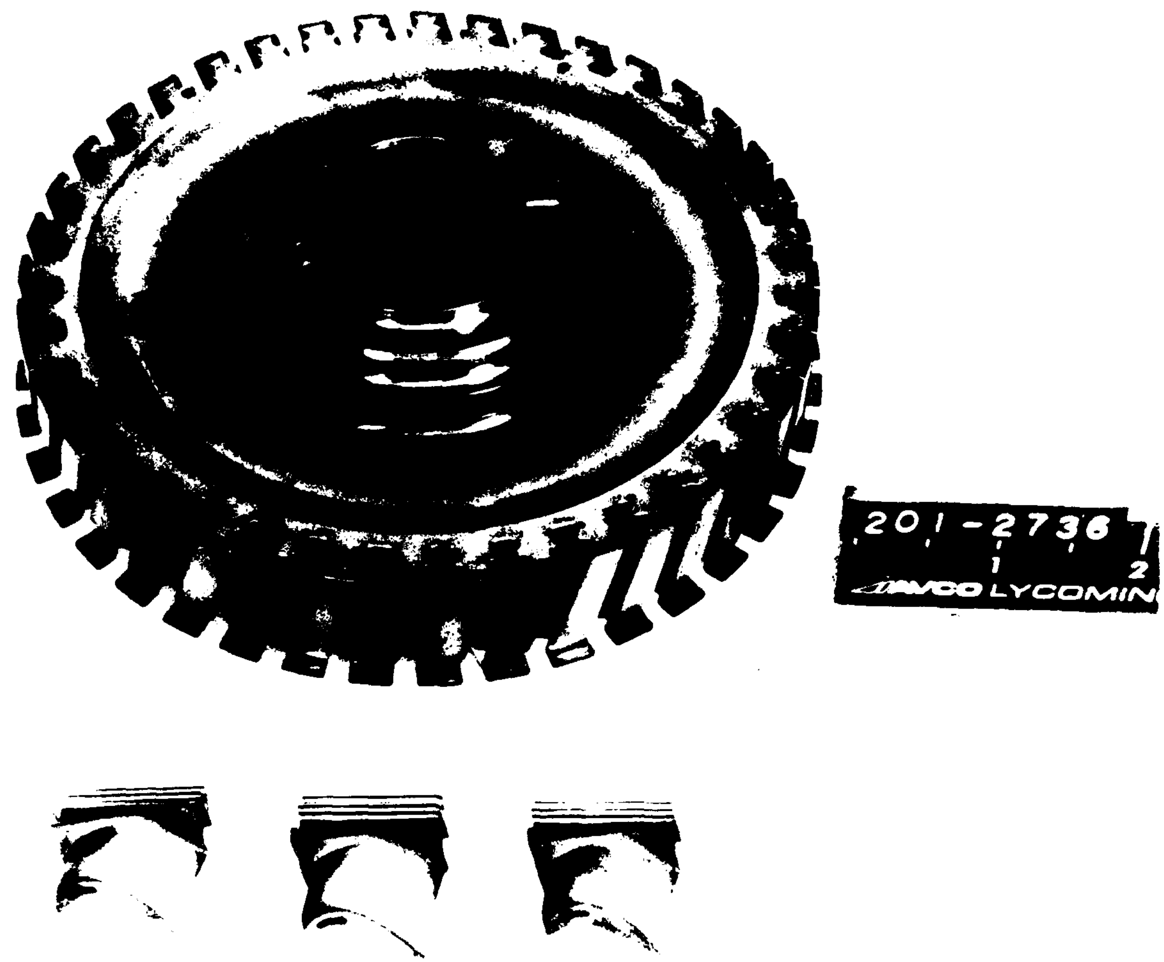

Figure 65. Gas Producer Turbine Di[illegible] and Selected Blades.

Figure 66. Combustor and Rear Bearing Support Housing (Front View).

Figure 67. Combustor and Rear Bearing Support Housing (Arrow Denotes Crack).

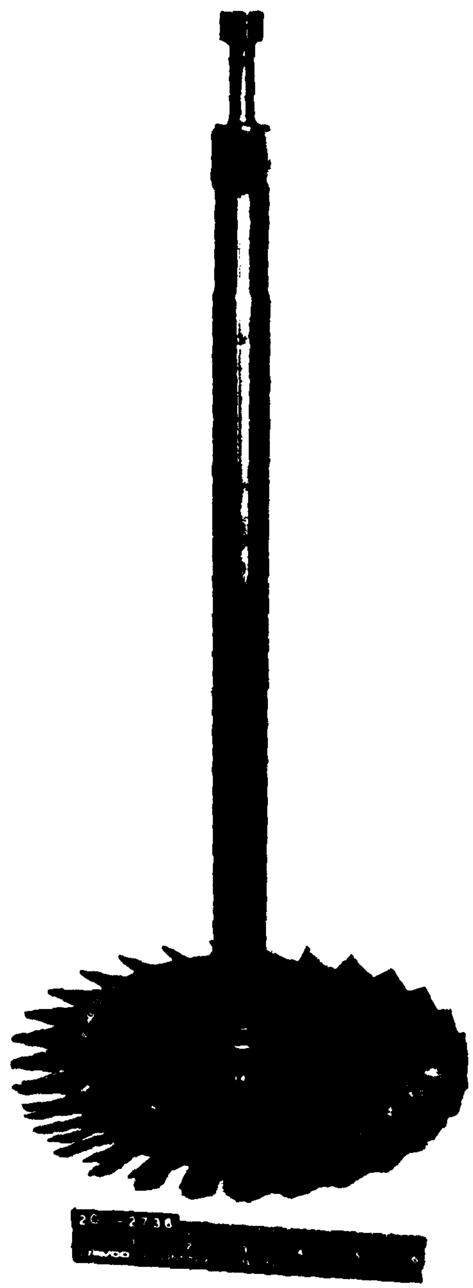

Figure 68. Power Turbine Rotor and Shaft Assembly.

Figure 69. Power Turbine Rotor.

Fuel Manifold, P/N 4-301-042-04

Functional bench testing of the fuel manifold revealed a 62 percent (10 percent maximum allowable) spread in nozzle flow at approximately idle fuel flow. The fourth nozzle was found to be 46 percent low in flow. This manifold was replaced on the engine during the JP-5 demonstration testing.

Ignitor Plugs, P/N 1-300-348-05

The LPU 101 features twin ignition. One of the ignitor plugs was found to be non-functional due to a broken tip. See Figure No. 70.

The HPAPU power producer features an eight-nozzle fuel manifold with primary and secondary circuits. Ignitor plugs are aligned with nozzles No. 4 and 5 (22.5° on either side of the 6-o'clock position). Starting fuel is provided by the primary circuit of the manifold. The combination of the partially blocked number four fuel nozzle coupled with an inoperative ignitor plug is suspected to have compromised the results of the altitude starting test. The location of the discrepant ignitor plug is not known nor is the precise time in the test when the plug failed. If the inoperative ignitor plug was aligned with the functioning fuel nozzle, the operating ignitor plug would have been aligned with a fuel nozzle that was 46 percent low in primary fuel flow. This combination would produce a starting characteristic as demonstrated during the 25,000-foot testing, namely: An initial reluctance to light followed by an overtemperature condition. The starting fuel schedules metered by the electronic fuel controls would have compensated for this hardware deficiency by metering an initially rich condition to achieve combustion followed by a reduction in fuel flow to limit the temperature.

3.3 ENDURANCE TESTING.

The 100-hour endurance demonstration was conducted at Sundstrand on the second HPAPU system using power producer S/N 202.

The ten simulated main engine starts required as part of the environmental testing on the first HPAPU system were also conducted at Sundstrand and are described in this section.

LPY 101-700, S/N 202, was assembled from parts list 4-005-000-1. For acceptance testing, the power producer was mated to an LTS 101-600A2 gearbox. Power was absorbed by a Lycoming LTCT2040 waterbrake. The initial run, consisting of 3.63 hours of operation, was completed on 31 August 1979.

Figure 70. Ignitors (Arrow Denotes Broken Igniter Tip).

This initial run was followed by disassembly for inspection. After inspection the power producer was reassembled in accordance with Test Assembly Memorandum (TAM) No. 9539-003, dated 6 September 1979. The power producer completed final acceptance testing on 3 October 1979. The test time was 4.58 hours, and it was shipped to Sundstrand for assembly into the HPAPU Demonstrator.

Parts List

The HPAPU Demonstrator is depicted by Sundstrand Drawing EP2626-6610. The unit consisted of the following major components:

EP2626-6310	Gearbox Assembly Consisting of
EP2626-6460*	Accessory Gearbox Assembly
EP2626-6311	Adapter Gearbox Assembly
EP2626-6626	Avco Lycoming LPU 101-700 Power Producer
EP2626-7030	Inlet Scroll
EP2626-335*	Load Compressor
716069*	Generator, Model 60EG01
5004780*	Motor Assembly, Electric
EP2626-7420*	Heat Exchanger
724707*	Duct, Heat Exchanger
724392*	Reservoir Assembly
5001249*	Gear Fuel Pump Assembly
EP2626-7085	Fuel Control
724260*	Electronic Controller
718564*	Generator Control Unit

Components indicated (*) were previously designed and developed by Sundstrand and are considered Proprietary.

Inspection

Major components for the two assembled HPAPU's were subjected to either an acceptance test or bench functional test prior to APU assembly. Component detail parts of the two assembled units were dimensionally inspected and non-destructively tested per established Sundstrand inspection standards and procedures.

HPAPU Weight

HPAPU Demonstrator Unit No. 1 weight (less controller) after test was 586 pounds. This weight included all undrainable fluid which remained in the APU after test.

Photographs

Photographs (Figures 71 and 72) of the completely assembled HPAPU were taken prior to the test.

Accuracy of Data

Test Facility Instrumentation listed in Table 15, was calibrated in accordance with established Sundstrand procedures and is traceable to the National Bureau of Standards.

Test Equipment

Test Stand Equipment

The test cell used for the HPAPU Demonstrator testing is depicted on Sundstrand Drawing EP5508-1-1 and shown schematically on Figures 73 and 74. The principal components included:

EP5508-2-1	Engine Mount Assembly
EP5508-3-1	Inertia Simulator Assembly
EP5508-5-1	Load Bank Assembly
EP5508-7-1	HPAPU Fuel System
EP5161-607-05-17	Test Cell Electrical Set-Up, which includes:
EP5161-607-05-13	HPAPU Control Console
EP5161-607-05-14	Facility Control Console
EP5161-607-05-15	Instrumentation Console
EP5161-607-05-16	Brush Recorders

The Inertia Simulator Assembly, which was employed for the HPAPU main engine start cycle portion of the testing, is an existing Sundstrand system currently in use in the F-16 Engine Start System program for simulating inertial characteristics of the F100 Engine.

An Avco Lycoming exhaust diffuser and calibrated test bellmouth was used for all HPAPU testing.

TABLE 15. INSTRUMENTATION (SHEET 1 OF 2)

Description	Range	Accuracy	Visual	Recording	Digital Print Out
Speed, Gas Producer	0 to 100%	$\pm$ .7%	X	X	X
Speed, Power Turbine (No. 1)	0 to 50,000 RPM	$\pm$ .7%			X
Speed, Power Turbine (No. 2)	0 to 50,000 RPM	$\pm$ .7%		X	X
Temperature, Power Turbine Inlet	0 to 200°F	$\pm$3%	X	X	X
Flow, Fuel	0 to 2 GPM	$\pm$1.7%	X	X	X
Temperature, Fuel In	-65°F to 150°F	$\pm$3%			X
Pressure, Fuel In	0 to 30 PSIG	$\pm$1.2%	X		X
Differential Pressure, Engine Inlet	0 to 20 in H_2O	$\pm$1.2%			X
Temperature, Engine Inlet	-65°F to 150°F	$\pm$3%			X
Pressure, Test Cell	0 to 20 PSIA	$\pm$1.2%			X
Temperature, Engine Oil Out	-65°F to 500°F	$\pm$3%		X	X
Pressure, Engine Oil In	0 to 100 PSIG	$\pm$1.2%			X
Vibration, Engine Radial	0 to 300 G	$\pm$5%	X	X	X
Vibration, Engine Axial	0 to 300 G	$\pm$5%	X	X	X
Pressure, Compressor Inlet	0 to 20 PSIA	$\pm$1.2%			X
Temperature, Compressor Inlet	-65°F to 150°F	$\pm$3%			X
Pressure, Compressor Outlet	0 to 100 PSIA	$\pm$1.2%		X	X
Temperature, Compressor Outlet	-65°F to 150°F	$\pm$3%			X
Differential Pressure, Mass Flow In				X	
Pressure, Mass Flow Out					X
Vibration, Radial, Compressor	0 to 300 G	$\pm$5%	X		X
IGV Position	-15° to +85°	-			X
Surge Valve Position	0 to 90°	-			X
Electrical Load, Generator	0 to 100 KVA	$\pm$1 KVA	X	X	X
Frequency, Generator	380 to 420 Hz	$\pm$1 Hz	X	X	X
Oil Flow, Engine Aft Bearings	0 to 1 GPM	$\pm$1.7%	X		X

TABLE 15. INSTRUMENTATION (SHEET 2 OF 2)

Description	Range	Accuracy	Visual	Recording	Digital Print Out
Temperature, Heat Exchanger Oil In	-65°F to 300°F	±3%			X
Temperature, Heat Exchanger Oil Out	-65°G to 250°F	±3%			X
Flow, Heat Exchanger	0 to 20 GPM	±1.7%			X
Differential Pressure, Heat Exchanger		0 to 50 PSID			X
Voltage, Electric Starter	0 to 30 Volts	±1%			X
Current, Electric Starter	0 to 1000 Amps	±1%			X
Pressure, Engine Lube Oil Supply	0 to 100 PSIG	±1.2%		X	X
Pressure, APU Gearbox Supply	0 to 500 PSIG	±1.2%		X	X
Pressure, Test Gearbox Supply	0 to 150 PSIG	±1.2%			X
Pressure, Test Gearbox Lube Jets	0 to 50 PSIG	±1.2%			X
Pressure, Gearbox Internal	0 to 10 PSIG	±1.2%			X
Vibration, Gearbox Horizontal	0 to 300 G	±5%	X		X
Vibration, Gearbox Vertical	0 to 300 G	±5%	X		X
Switch, Low Oil Pressure	OFF - ON	-	X		
Switch, Low Oil Quantity	OFF - ON	-	X		
Switch, High Oil Temperature	OFF - ON	-	X		
Speed, Air Turbine Motor	0 to 10,000	± .7%		X	
Speed, Inertia Wheel	0 to 10,000	± .7%		X	
Barometer	AMBIENT PRESSURE				X
Temperature, Ambient	-65°F to 150°F	± .3%			X
Hourmeter	-	-	X		

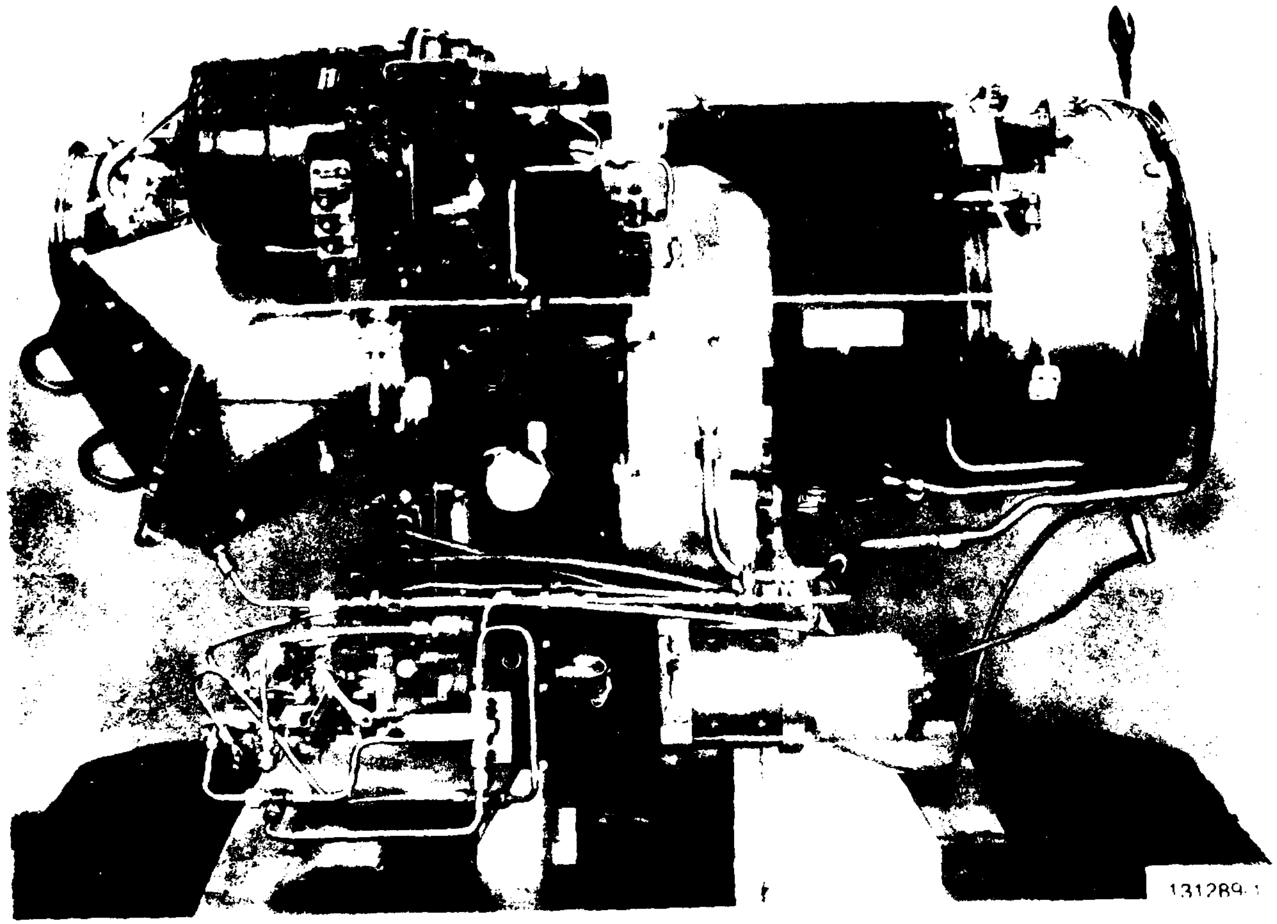

Figure 71. HPAPU Assembly - Side View.

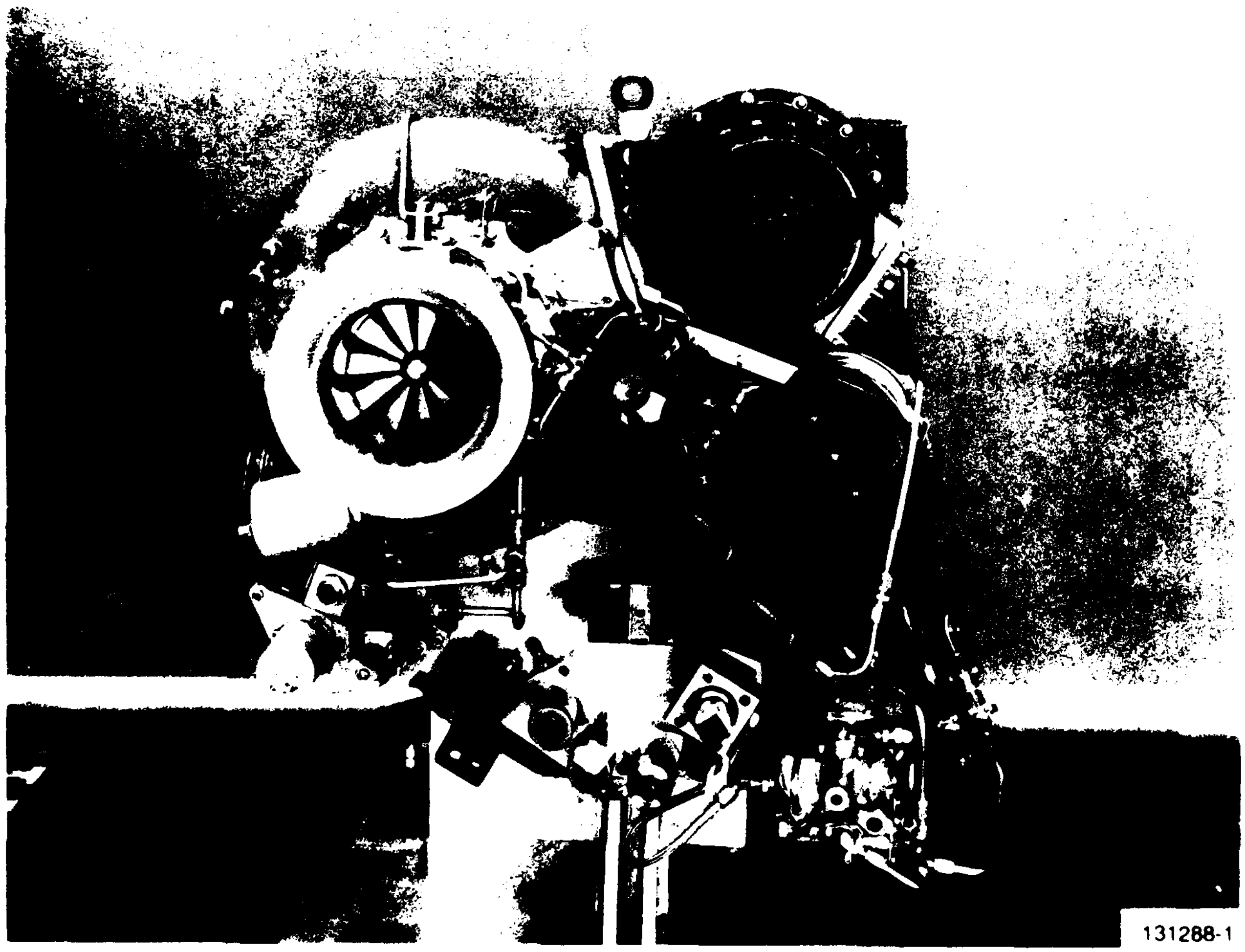

Figure 72. HPAPU Assembly - Front View.

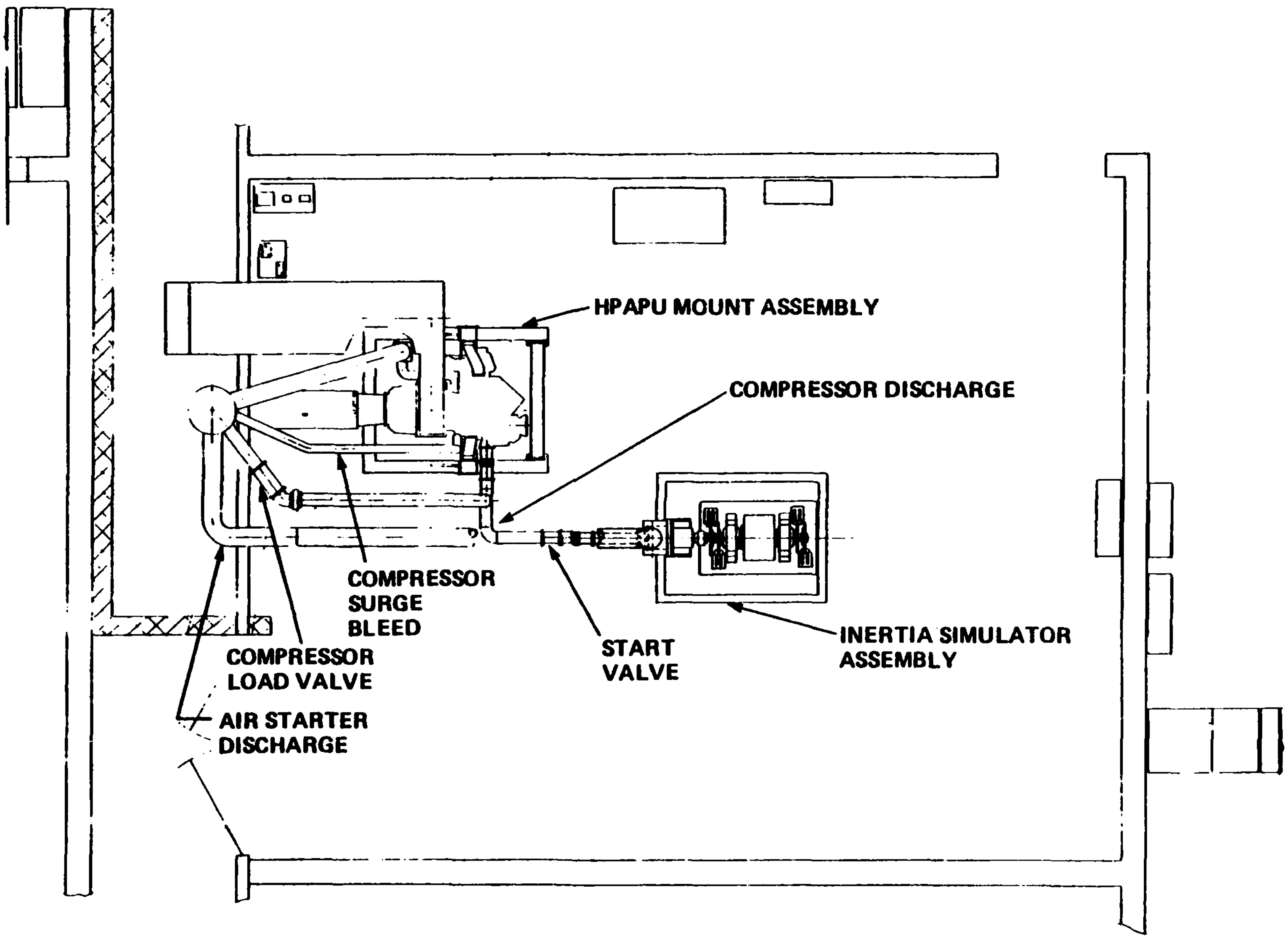

Figure 73. HPAPU Facility Schematic.

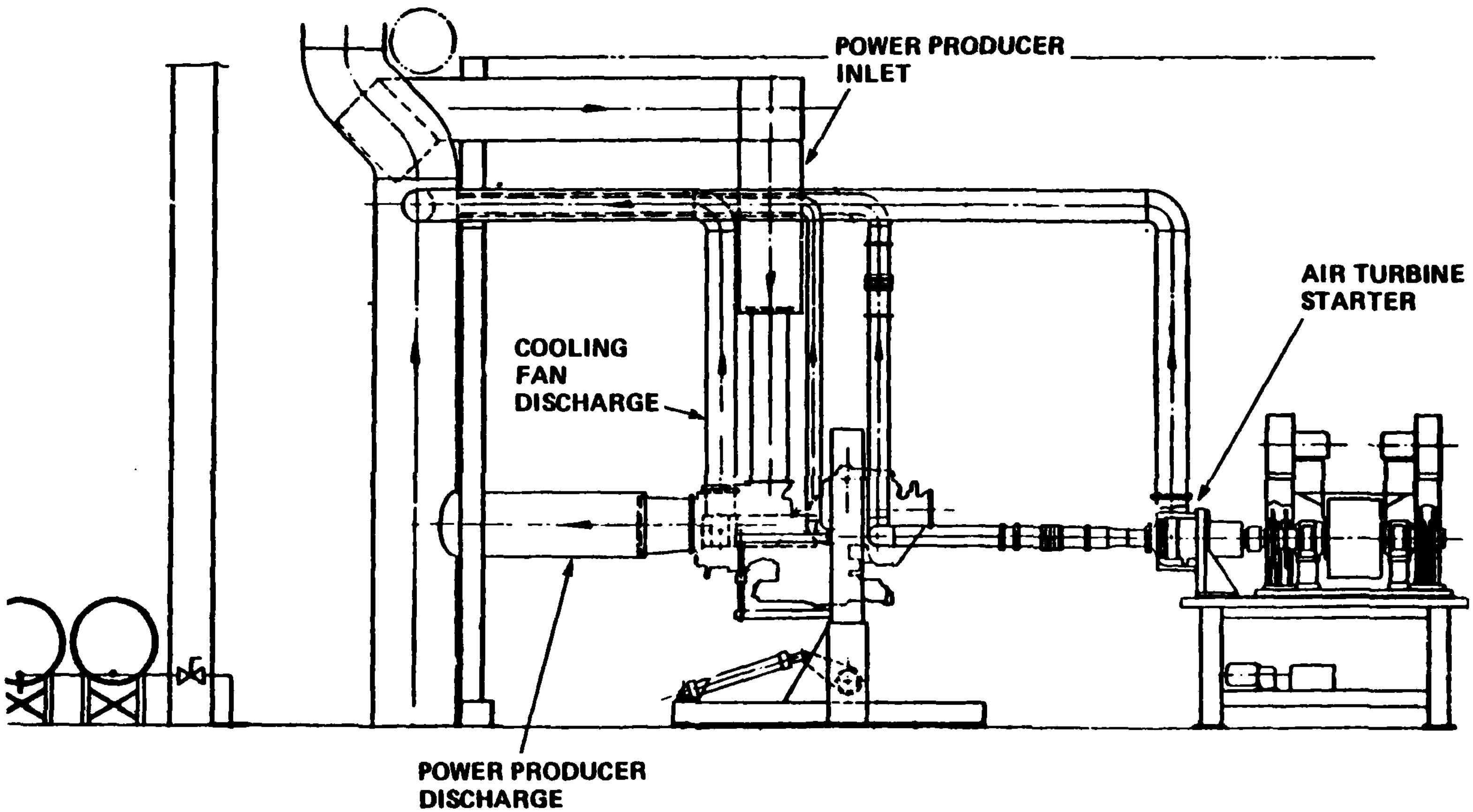

Figure 74. HPAPU Test Facility Schematic.

The APU load compressor was loaded by the system shown schematically in Figure 75. Air from the compressor could be used to drive the air turbine starter during a simulated main engine start cycle or could be routed through the load valve, a device for controlling air flow rate and pressure at the compressor. During endurance testing the compressor air was routed through the load valve at all times except during main engine starts.

Air flow rate through the system was controlled by the manually operated guide vanes at the compressor inlet.

Test Methods

Fuels and Lubricants

The HPAPU Demonstrator was operated on JP-4 Aviation Fuel in accordance with Specification MIL-T-5624J. Lubricating oil was in accordance with Specification MIL-L-7808.

Test Conditions

All testing was conducted at prevailing test laboratory ambient conditions. Demonstrated Peak Power was at the maximum power absorption capability of the Test Equipment portion of the HPAPU.

Steady-State Data

Steady-state digital printout data as listed in Table 15 were recorded by an Automated Data Acquisition System (ADAS). During endurance cycling, ADAS data were recorded at each load setting, a total of four times per cycle. During full load endurance, ADAS data were taken every one-half hour. Visual instrumentation listed in Table 15 was also provided.

Transient Data

Transient data listed in Table 15 were recorded by two Brush Recorders. A one second timer was operating whenever the recorder was running.

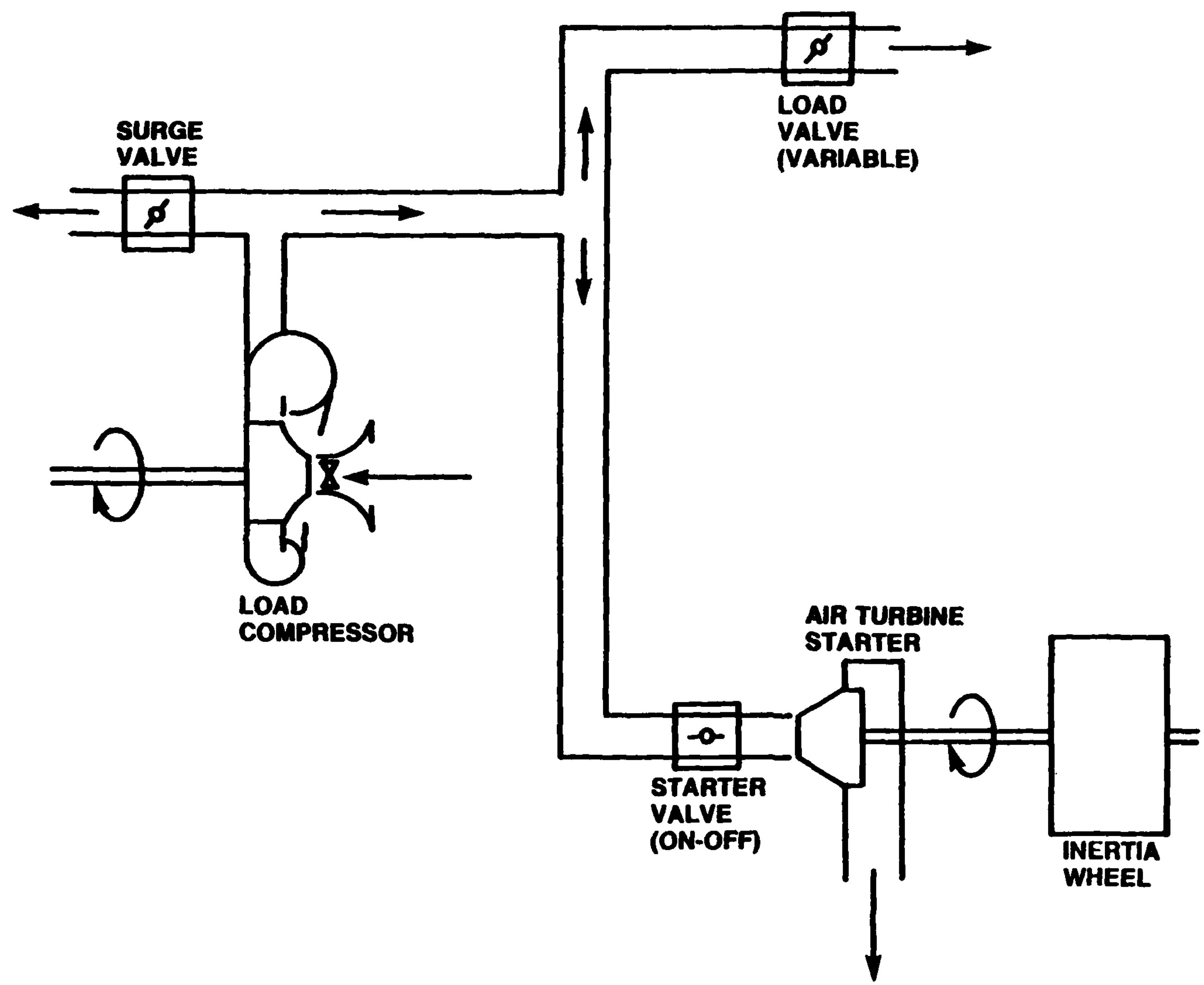

Figure 75. HPAPU Load Air Schematic.

For each test segment, the recorder traces are identified by the following information:

1. Test Title and Endurance Cycle Number, if applicable
2. Test Stand Number
3. Date and Time
4. Title and Serial Number of Unit
5. Trace Identification and Calibration

Test Description

Two HPAPU Demonstrator units were scheduled for testing. Unit No. 1 was scheduled to perform main engine start cycles at test cell ambient conditions using the inertia test stand to simulate main engine inertia characteristics. Unit No. 2 was scheduled to perform 100 hours of endurance testing followed by a formal demonstration for Government representatives:

Unit No. 1

Unit No. 1 was assembled and a system checkout was performed. Upon successful completion of the system checkout, 10 main engine start cycles were performed using the inertia test stand facility.

Unit No. 2

Unit No. 2 was assembled and a system checkout was performed. Upon completion of a successful system checkout a 100-hour endurance test was performed. Subsequently, a formal demonstration, which included peak power conditions, load transients, and main engine start cycles, was performed for representatives of government and industry.

Test Operating Conditions

Lubrication System

The lubrication system fcr the HPAPU Demonstrator used during testing is schematically depicted by Figure 76. Lubrication system data were recorded in accordance with the listing of Table 15.

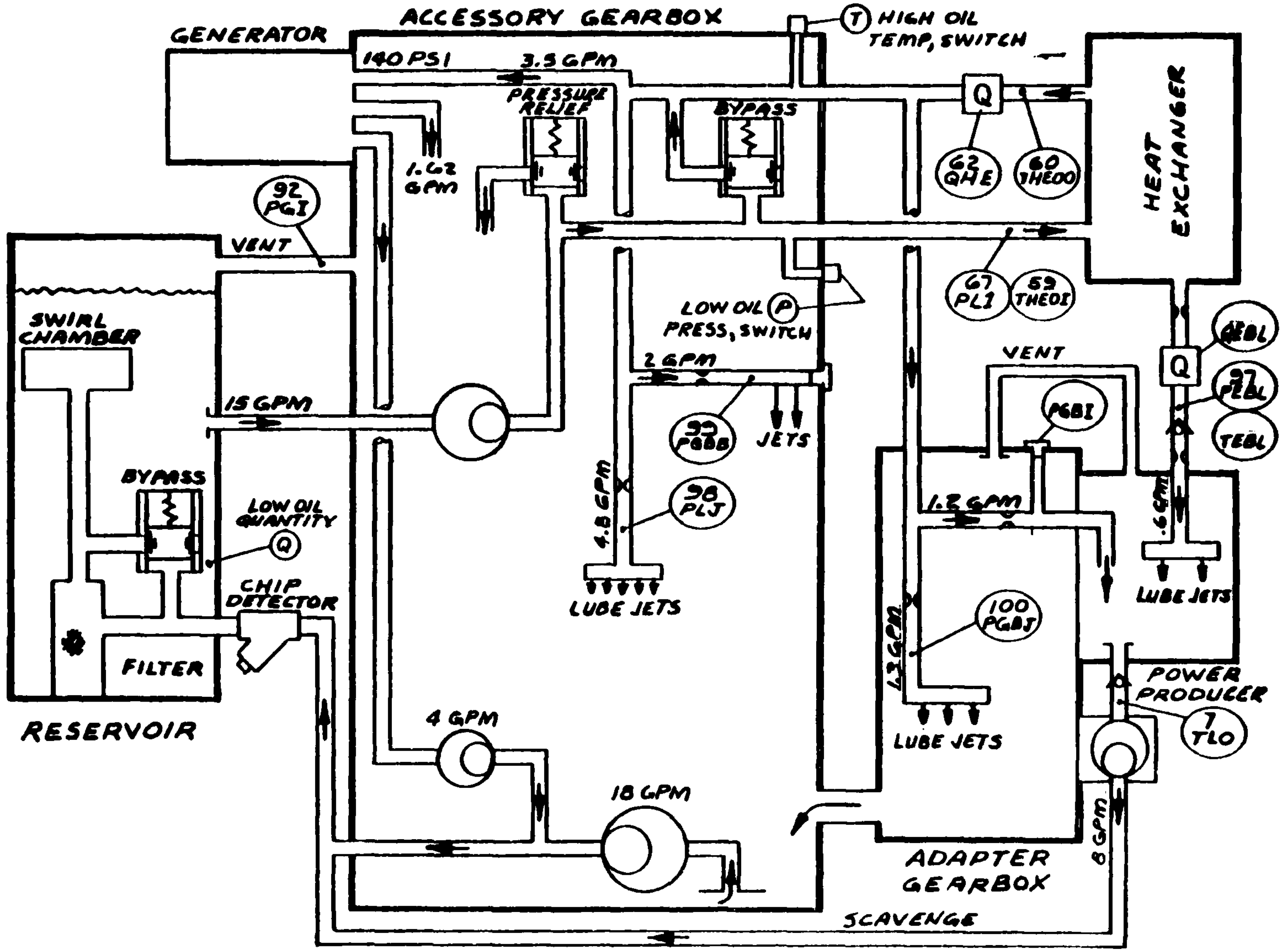

Figure 76. HPAPU Lube Schematic.

The lube reservoir incorporated upper and lower level sight glasses. The system also incorporated an auxiliary reservoir with high- and low-level switches and a sight column to permit adding measured amounts of oil during operation.

Lube levels were checked during normal shutdowns and oil was added and recorded whenever the lube level reached the lower sight gage. During the continuous operation testing, oil was added as indicated by the level switches.

Oil samples were taken and spectrographically analyzed following the testing of HPAPU No. 1 and during and after the 100-hour endurance test of HPAPU No. 2. Table 16 is a report of the results of those analyses. The 3 oil samples submitted to this EWR were sent to Analysts, Inc., for the spectrographic oil analysis (SOAP). Data from that laboratory are given in Table 16. The levels are in general relatively low. Only the quantity of tin (Sn) is relatively high.

Fuel System

A fuel sample was taken before HPAPU No. 1 testing and the specific gravity was 0.755.

A sample was also taken after the endurance test of HPAPU No. 2. Its specific gravity was 0.746.

TABLE 16. SPECTROGRAPHIC OIL ANALYSIS DATA FOR OIL SAMPLES FROM HPAPU TESTING, PPM

Sample No. Date Source	1 11/30/79 After Run # APU #1	2 2/28/80 After Cycle 25 APU #2	3 3/4/80 After 100 Hour Endurance Test APU #2
Al	0	0	0
Cr	0	0	0
Cu	0.3	0.1	0.1
Fe	1.0	0.3	0.2
Pb	1.3	0.5	0
Mg	0	0.1	0
Ni	0	0.2	0
Si	4.1	0.8	0.5
Ag	0.7	0.7	0.7
Sn	11.6	10.3	6.9
Zn	0	0	0

Note: Spectrographic Oil Analysis for MIL-L-7808 Oil Samples from HPAPU - Ref. EWR 15,273

Accreditable Test Time

During the cyclic portion of the endurance test, time in excess of 10 minutes into each endurance cycle was accredited. During the steady-state peak power portion of the endurance test, only continuous running time at peak power was accredited.

Barometer Reading

The Sundstrand Automatic Data Acquisition System provides a Barometer reading automatically for each recorded data point.

Test Logs

Logs were kept of all test stand activity. The log sheets kept during cycling endurance included cycle number, time and date, and related data. The log sheets kept during full load endurance noted start-up and shutdown times, oil additions, and the recording of ADAS data every half hour.

Test Procedure and Results

HPAPU No. 1

The system was assembled per Sundstrand Drawing EP2626-6610 and the unit was installed in the test cell.

A system checkout was performed which included starter motoring checks, leakage checks, instrumentation checks, lubrication pressures and temperatures, a vibration survey and pneumatic and electrical loading checks.

After the system checkout the unit successfully demonstrated 10 main engine starts using the inertia test stand facility.

Following completion of the 10 starts, the unit was shut down. There was no visual damage or leakage from the unit.

The unit was removed and shipped to Lycoming.

HPAPU No. 2 was assembled, installed and the system checked out similarly to HPAPU No. 1. The 100-hour endurance test was to include 50 hours of endurance cycling in accordance with Figure 77 and 50 hours of uninterrupted operation at peak power. Peak power was defined as the full load or maximum power absorption capability of the test equipment portion of the APU.

The 100-hour endurance test was run in the following sequence:

a) Cycling Endurance cycles, Numbers 1 through 3, one hour each.

b) Full load Endurance, 50 hours.

c) Cycling Endurance, Cycle Numbers 4 through 50.

An additional one hour cycle was run during a shutdown in the 50 hour full load test. The 50 hours of full load operation were to have been continuous uninterrupted running, but at 34 hours and 43 minutes into the test, the unit was shut down due to an indication on the chip detector in the lubrication scavenge line. The chip detector was the type where fuzz, as opposed to a solid chip, could be burned off by application of an electrical charge. The operator had attempted fuzz burn-off three times without success. The chip detector element was removed and no significant chip was found. The facility wiring was visually inspected and it was found that the insulation on the wire to the chip detector had become frayed, allowing a short circuit and a false indication of a chip. It was agreed, if the wiring problem was the cause of the shutdown, it did not constitute failure of the test article and should not penalize the test program. The wiring was repaired, a one hour cycle run as checkout, and full load endurance was resumed at 34 hours and 43 minutes with Avco Lycoming and U.S. Air Force concurrence.

The 50-hour requirement and the last 47 endurance cycles were completed without additional indication from the chip detector. A summary of the test log sheets of the cyclic portion of the endurance testing is shown on Table 17. Copies of the peak power portion are shown on Table 18. Also, copies of selected portions of the Brush recorder traces of Cycle 36, showing start-up, a simulated main engine start, ADAS data point conditions (as marked) generator load transients, full load operation, and shutdown are included in Figure 78. Copies of the four ADAS data printouts, recorded during a typical endurance cycle and an ADAS acronym key are shown on Table 19.

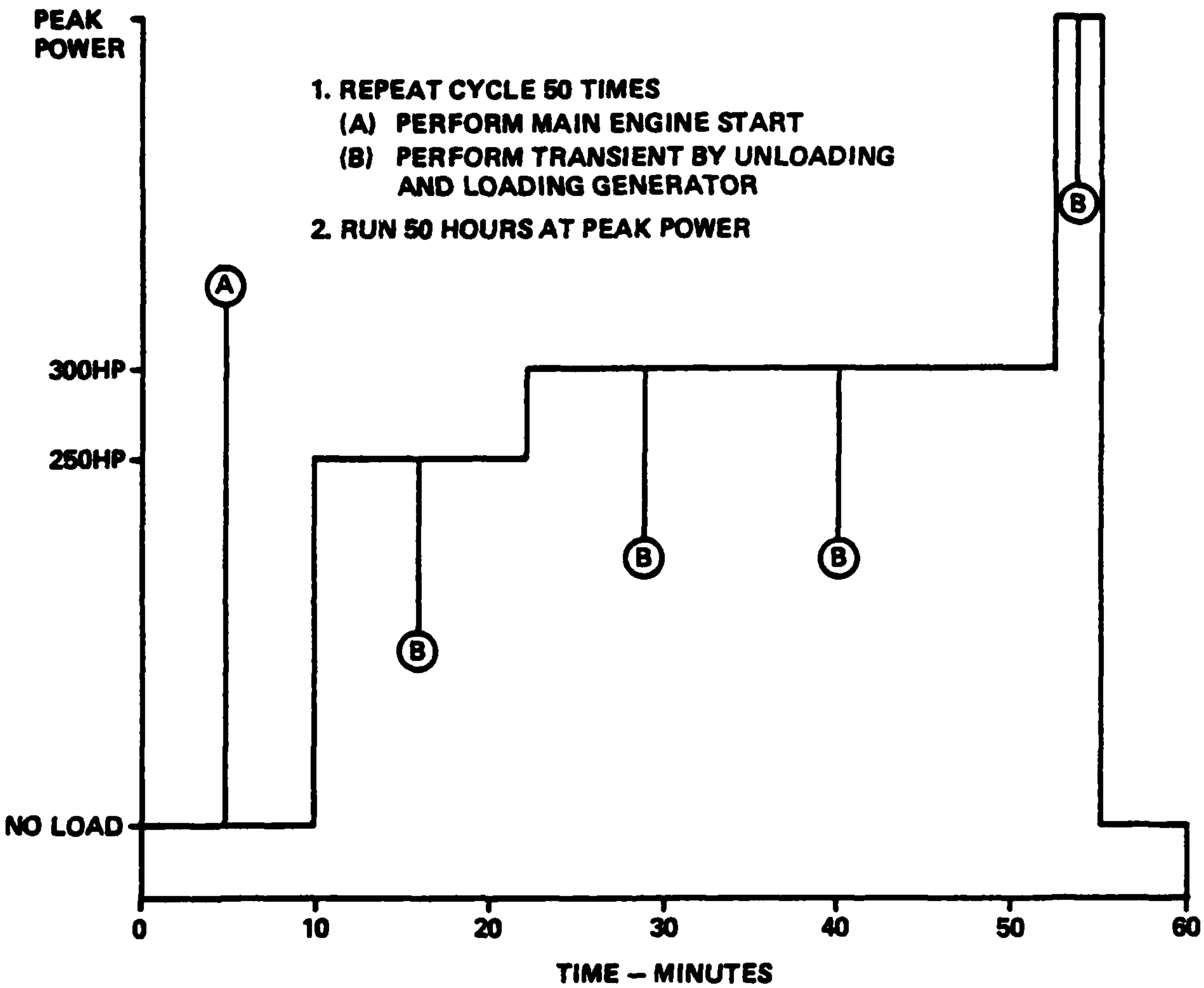

Figure 77. HPAPU Endurance Cycle.

TABLE 17. TEST LOG, HPAPU ENDURANCE TEST, CYCLIC
(SHEET 1 OF 2)

Cycle No.	Date	Start Time	End Time	Visual Inspect	Oil Added Or OK	Fuel Meter	Comment, Notes	Initial
1	2/5/80	10:55	11:55	OK	OK	248	Lost ADAS, Got only 1 point.	P.L.
2	2/6/80	09:25	16:05	OK	OK	287	Run in 3 segments, Ref Stand Run Nos. 58, 61, 62	P.L.
3	2/9/80	18:32	19:32	OK	OK	318		P.L.
Prior to Cycle 4						2520		
4	2/20/80	12:44	13:44	OK	OK	2550		P.L.
5	2/20/80	13:55	14:55	OK	OK	2581		P.L.
6	2/20/80	15:10	16:10	OK	OK	2611		P.L.
7	2/21/80	09:40	10:40	OK	OK	2641		P.L.
8	2/21/80	11:00	11:57	OK	OK	2671	Run in 2 segments	P.L.
8 (Ct)	2/21/80	13:54	13:58	OK	OK	2671	Ref Runs 80, 81	P.L.
9	2/21/80	14:00	14:10	OK	OK		Run in 3 segments	P.L.
9 (Ct)	2/21/80	14:45	14:56	OK	OK			
9 (Ct)	2/22/80	09:20	10:01	OK	OK	2702	Ref Runs 82,83,85	P.L.
10	2/22/80	10:40	11:40	OK	OK	2731		P.L.
11	2/22/80	12:45	13:45	OK	OK	2761	No ADAS	P.L.
12	2/22/80	14:00	15:00	OK	OK	2791		P.L.
13	2/22/80	15:30	16:30	OK	OK	2821		P.L.
14	2/22/80	16:40	17:40	OK	OK	2851		P.L.
15	2/25/80	09:10	10:10	OK	OK	2881		L.S.
16	2/25/80	10:20	11:20	OK	OK	2911		L.S.
17	2/25/80	11:30	13:30	OK	OK	2940		L.S.
18	2/25/80	13:30	14:30	OK	OK	2970		L.S.
19	2/25/80	14:35	15:35	DID NOT SHUT DOWN				P.L.
20	2/25/80	15:35	16:35	OK	OK	3029		P.L.
21	2/25/80	16:40	17:40	OK	OK	3059		P.L.
22	2/27/80	10:20	11:20	OK	??	3105		V.S.
23	2/27/80	15:25	16:25	OK	OK	3134		P.L.
24	2/27/80	16:45	17:45	OK	OK	3164		P.L.
25	2/28/80	08:30	09:30	OK	OK	3194		P.L.
26	2/28/80	09:40	10:45	OK	OK	3223		WEL
27	2/28/80	10:50	11:50	OK	OK	3253		WEL
28	2/28/80	13:00	14:00	OK	OK	3283		WEB?
29	2/28/80	14:30	15:30	OK	OK	3313		
30	2/28/80	15:45	16:45	OK	OK	3342		R.E.F.
31	2/28/80	16:55	17:55	OK	OK	3372		R.E.F.
32	2/29/80	09:10	10:10	OK	OK	3402	Change Controllers	L.S.
33	2/29/80	10:10	11:10	OK	OK	3232	Change Controllers	L.S.
34	2/29/80	11:30	11:45	OK	OK		Run in 2 segments	L.S.
34 (Ct)	2/29/80	12:40	13:15	OK	OK	3461	Runs 120, 121	L.S.
35	2/29/80	13:25	14:25	OK	OK	349.1		WEL

TABLE 17. TEST LOG, HPAPU ENDURANCE TEST, CYCLIC
(SHEET 2 OF 2)

Cycle No.	Date	Start Time	End Time	Visual Inspect	Oil Added Or OK	Fuel Meter	Comment, Notes	Initial
36	2/29/80	14:30	15:30	OK	1 inch ?	3521		L.S.
37	2/29/80	15:33	16:33	OK	OK	3550		P.L.
38	2/29/80	16:40	17:40	OK	OK	3580		?
39	3/3/80	08:25	09:25	OK	OK	3610		?
40	3/3/80	09:40	10:40	OK	OK	3640		P.L.
41	3/3/80	12:45	13:45	OK	OK	3669		P.L.
42	3/3/80	14:00	-	OK		-	Run as 2 segments	P.L.
42 (Ct)	3/3/80		16:30	OK	OK	3700	Ref Runs 130,133	P.L.
43	3/3/80	16:35	17:35	OK	OK	3729	Added 3/4" Oil (Make up for loss at switch port)	P.L.
44	3/3/80	17:45	18:45	OK	OK	3759		P.L.
45	3/4/80	08:45	09:45	OK	OK	3789		L.S.
46	3/4/80	09:50	10:50	OK	OK	381.8		W.E.L.
47	3/4/80	10:55	11:55	OK	OK	3848		L.S.
48	3/4/80	13:10	14:10	OK	OK	3878		W.E.L.
49	3/4/80	14:25	15:25	OK	OK	3907		P.L.
50	3/4/80	15:25	16:25	OK	OK	3937		P.L.

TABLE 18. TEST LOG, HPAPU ENDURANCE TEST, PEAK POWER
(SHEET 1 OF 6)

DATE	TIME	RUN TIME	EVENT, NOTES	INITIAL
2-6-80	2036	0	START 50 HR RUN	P.L
2/6	2044	8'	ADAS DATA POINT	P.L
2/6	2055	19	ADD OIL 1 5/8" IN SIGHT GLASS	P.L
2/6	2100	24	ADAS - NO RECORD	P.L
2/6	2111	35'	ADAS- DATA POINT 1	P.L
2-6-80	2135	1 hr	ADAS	L.W.
2-6-80	2200		ADAS	LW
2-6-80	2230	2 hrs	ADAS NO POINT	LW
2-6-80	2240		ADAS	LW
2-6-80	2300		ADAS	LW
2-6-80	2330	3 hrs	ADAS	LW
2-6-80	2400		ADAS	LW
2-7-80	0030	4 hrs	ADAS	LW
2-7-80	0100		ADAS ADD OIL 3" IN SIGHT GLASS	LW
2-7-80	0130	5 hrs	ADAS	LW
2-7-80	0200		ADAS	LW
2-7-80	0230	6 hrs	ADAS	LW
2-7-80	0300		ADAS	LW
2-7-80	0330	7 hrs	ADAS	LW
2-7-80	0400		ADAS ADDED 2¼" OIL	ED
"	0430	8 hrs	"	KS

TABLE 18. TEST LOG, HPAPU ENDURANCE TEST, PEAK POWER
(SHEET 2 OF 6)

DATE	TIME	RUN TIME	EVENT, NOTES	INITIAL
2-7-80	0500		ADAS	KS
"	0530	9 hrs.	ADAS	KS
"	0600		ADAS TEBL 128°F	KS
"	0630	10 hrs.	ADAS	KS
"	0700		ADAS TEBL 126°F	KS
"	0730	11 hrs.	ADAS TEBL 124°F Added 2 1/4" of Oil	KS
"	0800		ADAS	KS
"	0830	12 hrs.	ADAS	KS
"	0900		ADAS	KS
"	0930	13 hrs.	ADAS TEBL 127°F	KS
"	1000		ADAS START OIL FILL 10:00 Fall at 1020 hrs. 2" of oil	KS
"	1030	14 hrs.	ADAS	KS
"	1100		ADAS	KS
"	1130	15 hrs.	ADAS TEBL 135°F	KS
"	1200		ADAS	CT
"	1230	16 hrs.	ADAS TEBL 133°F	DM
"	1300		ADAS TEBL 133 Added 2" of oil 7808 oil	KS
"	1330	17	ADAS	KS
"	1400		ADAS	KS
"	1430	18	ADAS	CT
2-7-80	1500		ADAS TEBL 135°F	[illegible]

TABLE 18. TEST LOG, HPAPU ENDURANCE TEST, PEAK POWER
(SHEET 3 OF 6)

DATE	TIME	RUN TIME	EVENT, NOTES	INITIAL
2-7-80	15:30	19 Hrs.	ADAS	KS
"	16:00		ADAS	KS
	16:30	20 Hrs.	ADAS ADDED OIL 1⅛"	LW
2-7-80	1700	-	ADAS	LW
"	1730	21 Hrs	ADAS OUT	LW
	1755		ADAS	RH
	1800	1275'	ADAS	RH
	1830	22	ADAS	RH
	1900		ADAS	RH
	1905		ADAS	LW
	1930	23	ADAS ADDED OIL 2"	RH
	2000		ADAS	RH
	2004		ADAS	RH
	2030	24	ADAS	LW
	2033		ADAS	RW
	2100		ADAS	RH
	2130	25	ADAS	LW
	2200		ADAS	RW
	2230	26	ADAS ADDED OIL 1⅛"	RW
	2300		ADAS	RW
	2330	27	ADAS	RW

TABLE 18. TEST LOG, HPAPU ENDURANCE TEST, PEAK POWER
(SHEET 4 OF 6)

DATE	TIME	RUN TIME	EVENT, NOTES	INITIAL
2-8-80	2400		ADAS	RU
"	0030	28	ADAS	RU
"	0100		ADAS	RU
"	0130	29	ADAS ADD oil 1 3/4"	RU
"	0200		ADAS	RU
"	0230	30	ADAS	RU
"	0300		ADAS	RU
"	0330	31	ADAS	RU
"	0400		ADAS	RU
"	0430	32	ADAS ADD OIL 2 1/2"	D.M.
"	0500		ADAS	D.M.
"	0530	33	ADAS	D.M.
"	0600		ADAS	D.M.
"	0630	34	ADAS	D.M.
2-8-80	0642		MAG CHIP INDICATION (SEE LOG SHEET)	R.R.
2-8-80	0648		MAG CHIP INDICATION (SEE LOG SHEET)	R.R.
2-8-80	0656		MAG CHIP INDICATION (SEE LOG SHEET)	D.M.
2-8-80	0700		ADAS	D.M.
"	0707		mag chip indicator (see log)	D.M.
2/8	0725	2083.4	SHUT DOWN DUE TO CHIP DETECTOR	R.R.
2/8	-	-	CHANGED FILTERS, TOOK OIL SAMPLES	

TABLE 18. TEST LOG, HPAPU ENDURANCE TEST, PEAK POWER
(SHEET 5 OF 6)

DATE	TIME	RUN TIME	EVENT, NOTES	INITIAL
2-9-80	0805	RESET RUN CLOCK TO -0-	STARTED RUN #66	R.H.
	0810		ADAS	R.H.
	0835		ADAS ADDED OIL 2"	R.H.
	0900		ADAS	R.H.
	0930		[illegible]	R.H.
	1000		ADAS	R.H.
	1030		ADAS	R.H.
	1100		ADAS ADDED OIL 3 1/8"	RH
	1130		ADAS ADDED OIL 1 5/8"	RH
	1200		ADAS	RH
	1230		ADAS ADDED OIL 2 3/8"	RH
	1300		ADAS	RH
	1330		ADAS ADDED OIL 2 3/4"	RH
	1400		ADAS	RH
	1430		ADAS ADDED OIL 3"	RH
	1500		ADAS	RH
	1530		ADAS ADDED OIL 2 1/4	RH
	1600		ADAS	[illegible]
	[illegible]		[illegible] ADD OIL 1 3/4	

TABLE 18. TEST LOG, HPAPU ENDURANCE TEST, PEAK POWER
(SHEET 6 OF 6)

DATE	TIME	RUN TIME	EVENT, NOTES	INITIAL
2-9-80	5:00		ADAS	D.M.
"	5:30		NO ADAS. WORKING ON IT.	D.M.
"	5:35		ADAS OK AND TAKEN (ADD 2" OIL)	D.M.
"	6:00		ADAS	D.M.
"	6:30		ADAS 1½ oil	C.T.
"	7:00		ADAS	CT
"	7:30		ADAS 1" OIL	D.M.
"	8:00		~~ADAS~~ adas did not go thru computer	"
"	8:39 ~~7:00~~		adas did not go thru again ½ oil	CT
"	8:50		ADAS TAKEN	DM
"	9:00		ADAS PT	D.M.
"	9:30		ADAS ~~OIL~~	DM
"	9:40		1¼" oil	CT
"	10:00		ADAS PT	D.M.
"	10:30		ADAS PT ¾ oil	CT.
"	11:00		ADAS	DM
"	~~11:24~~			CT.
"	11:24	0920	ADAS	DM
"	11:31	0927 min	SHUT DOWN	[illegible]
"				

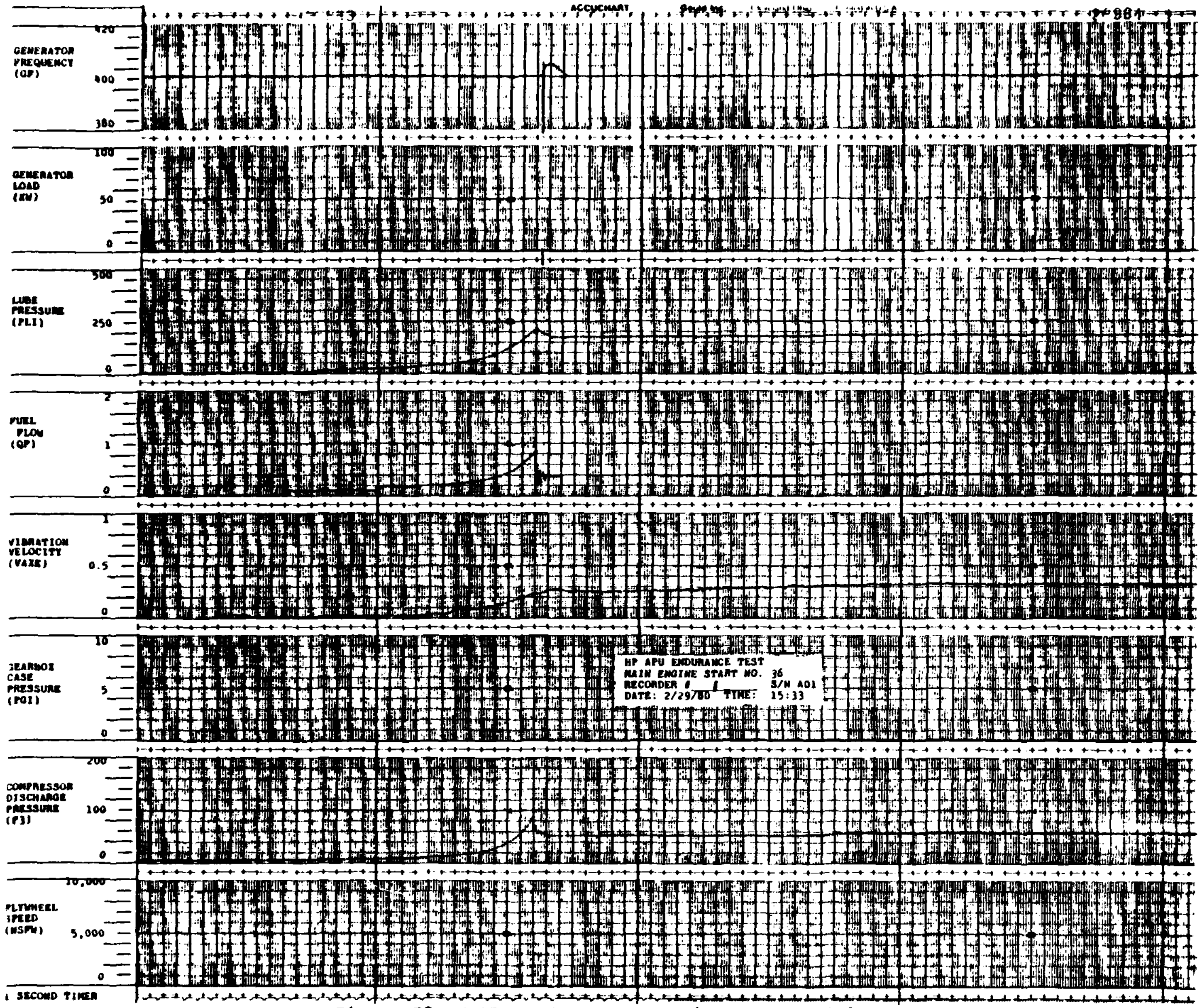

Figure 78. HPAPU Endurance Test (Sheet 1 of 15).

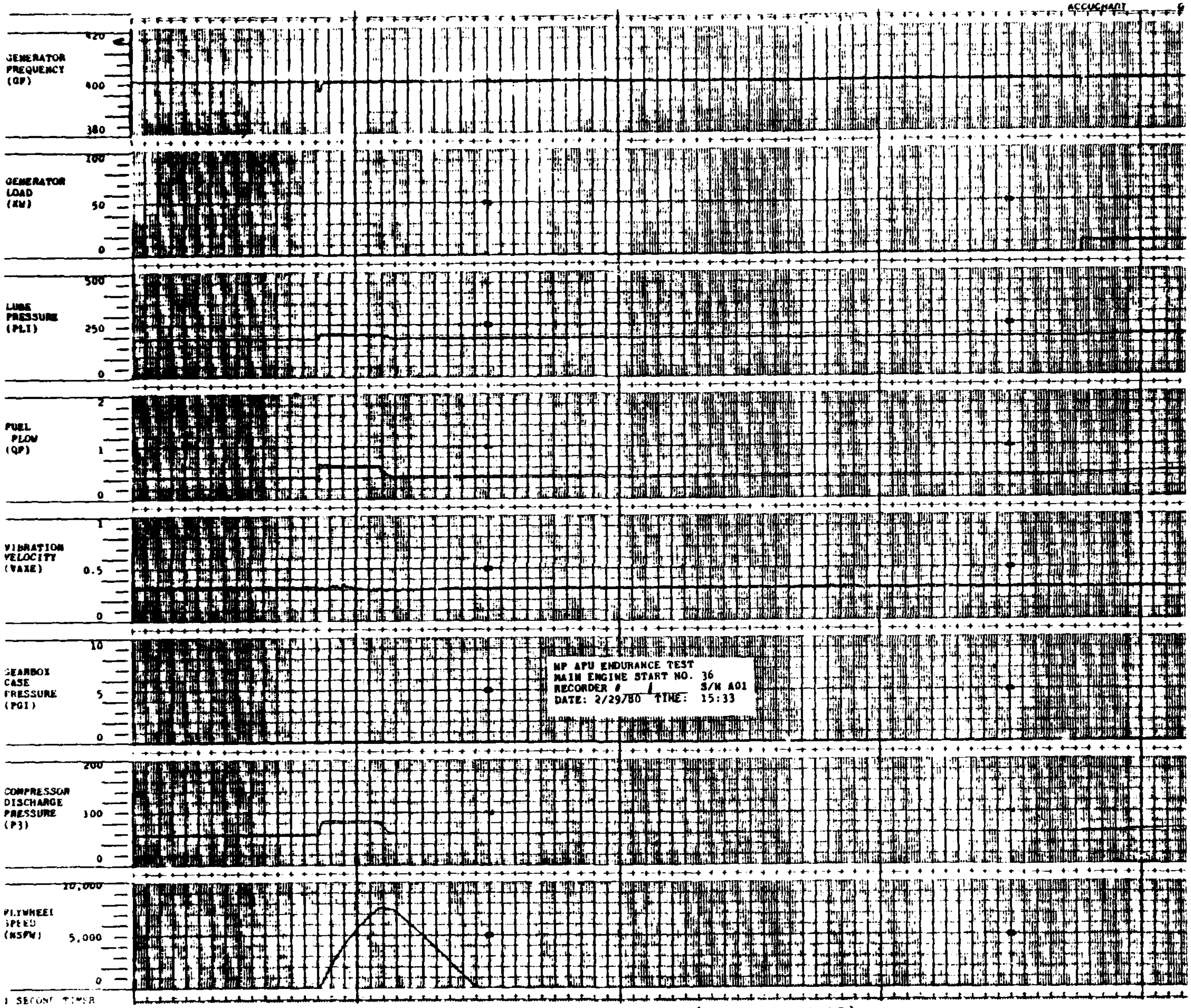

Figure 78. HPAPU Endurance Test (Sheet 2 of 15).

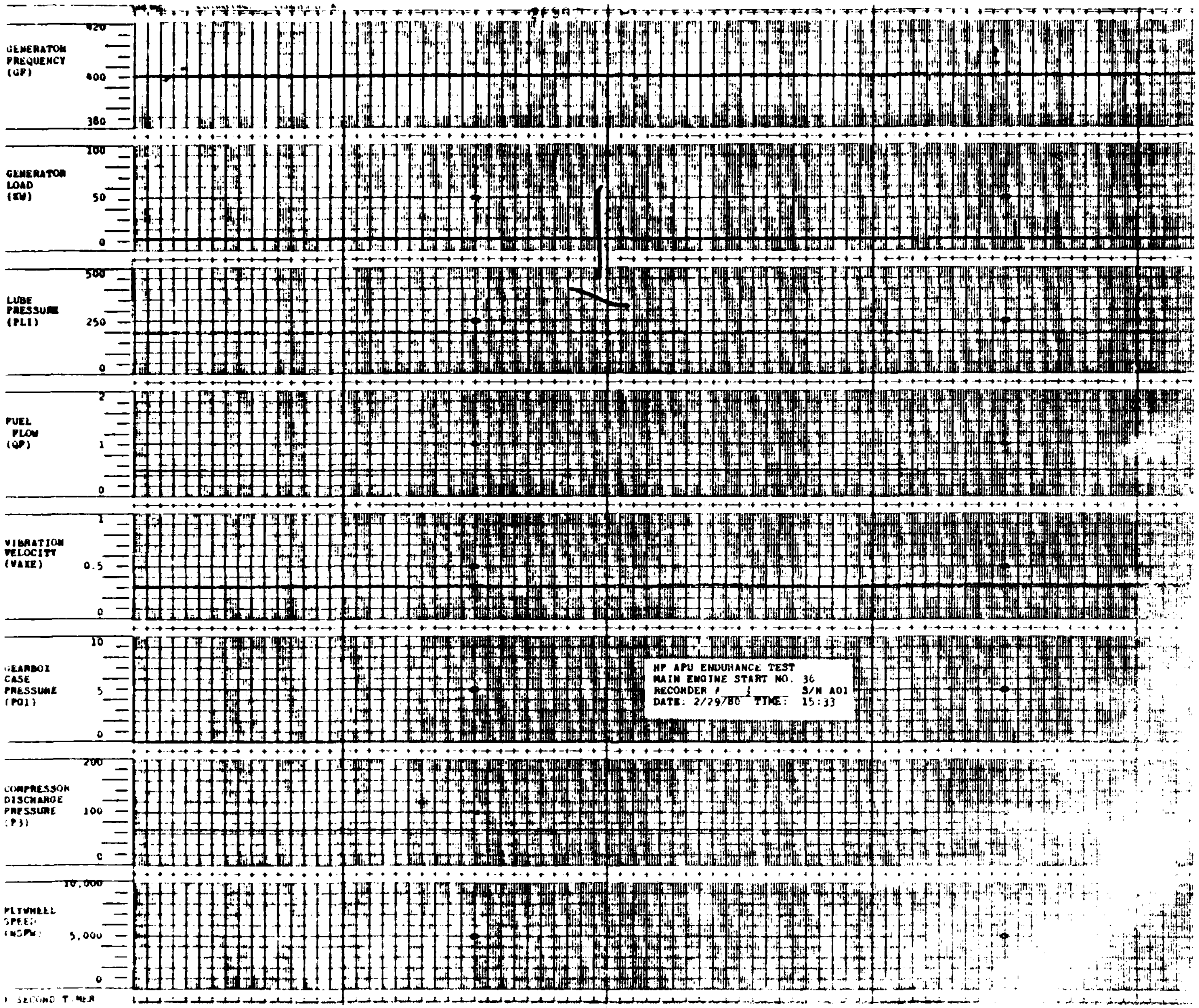

Figure 73. HPAPU Endurance Test (Sheet [illegible])

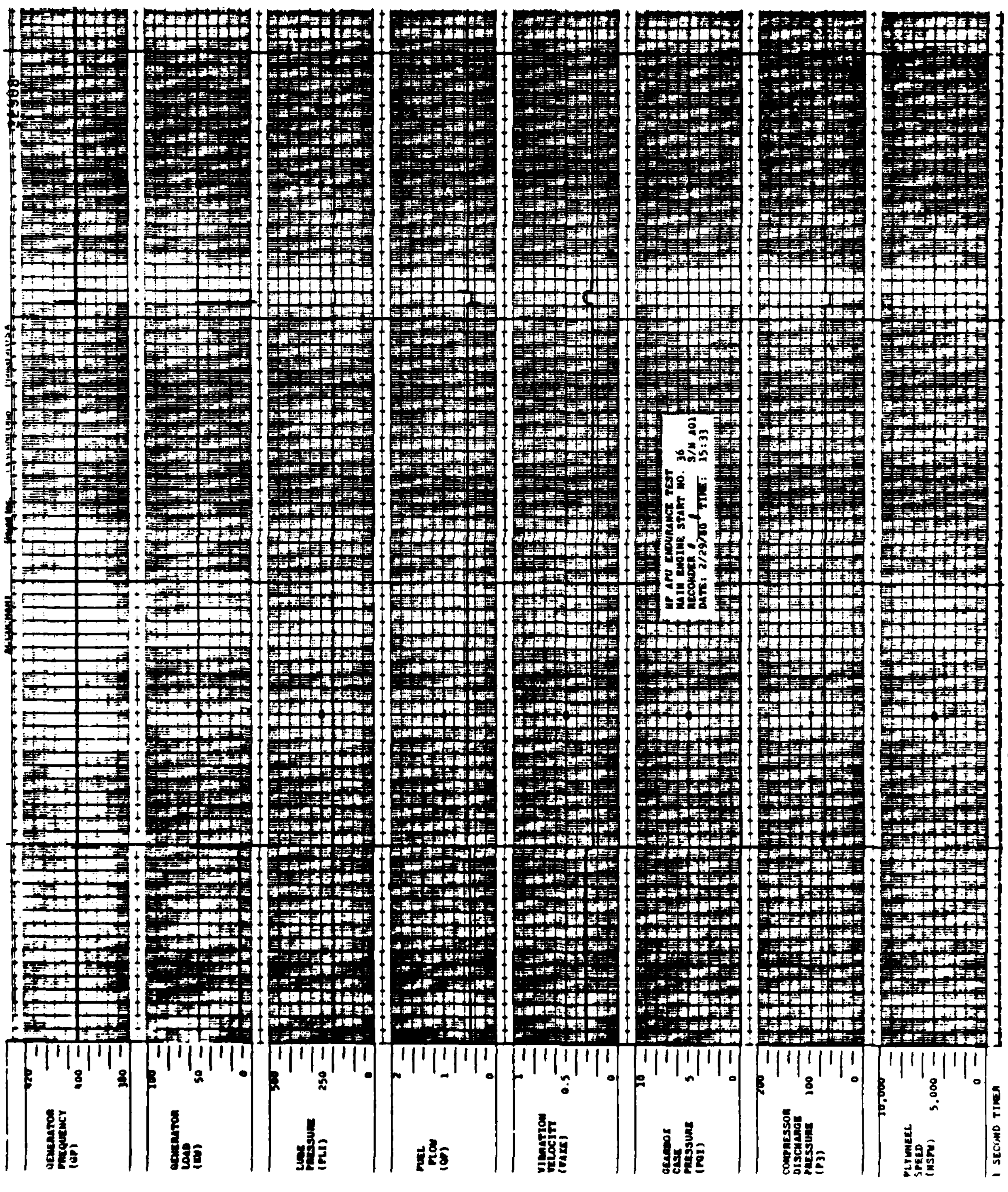

Figure 78. HPAPU Endurance Test (Sheet 4 of 15).

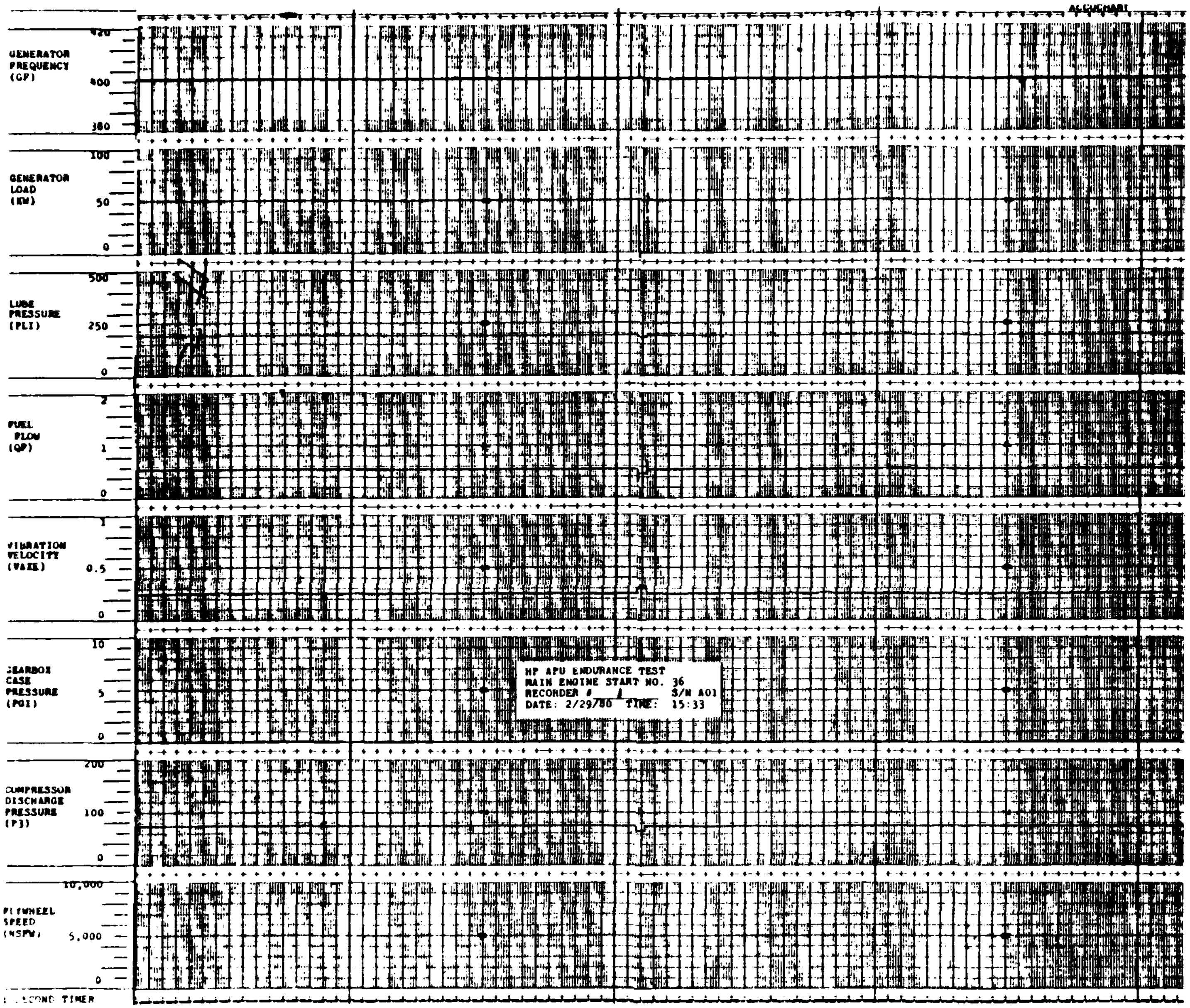

Figure 78. HPAPU Endurance Test (Sheet 5 of 15).

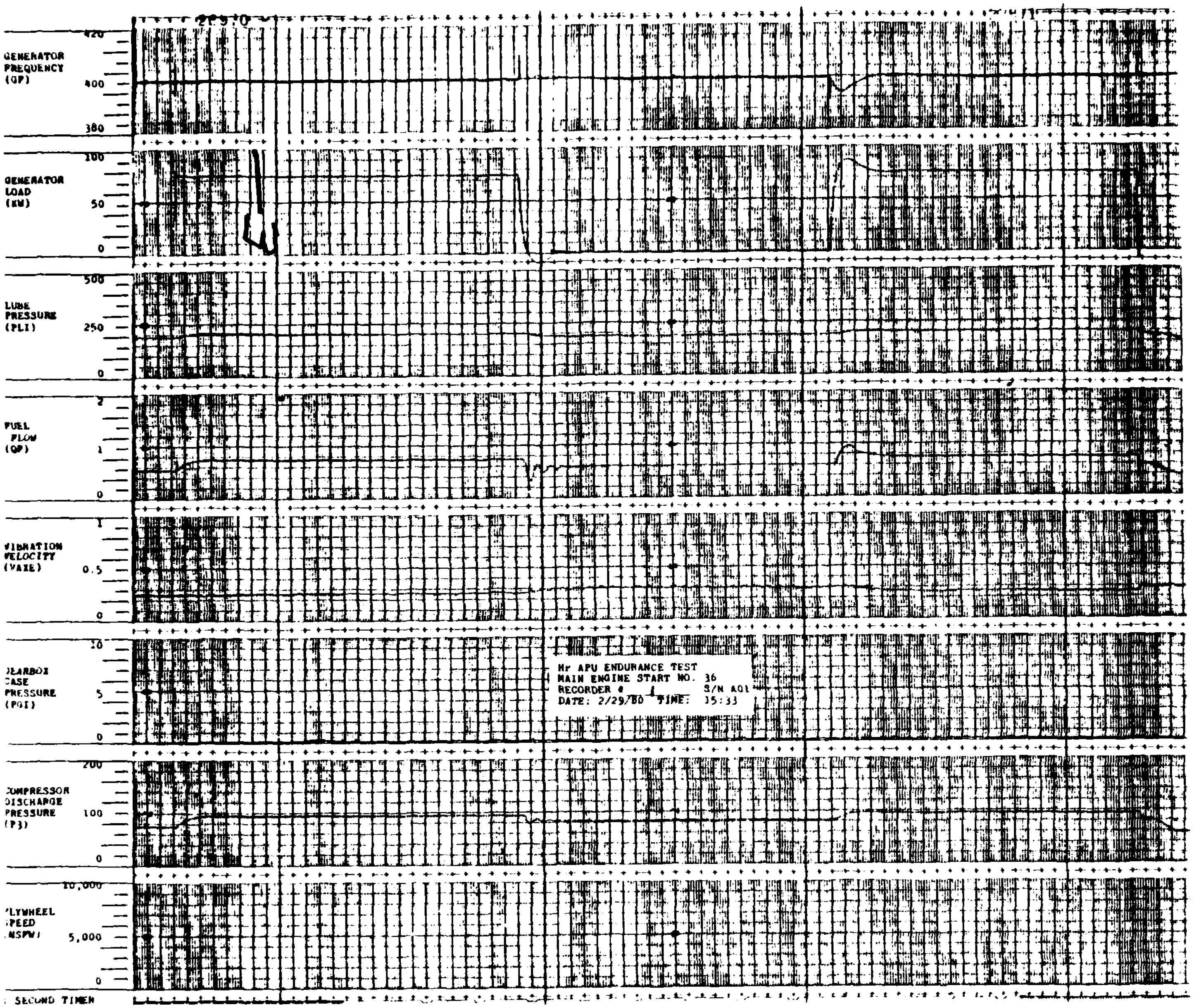

Figure 78. HPAPU Endurance Test (Sheet 6 of 15).

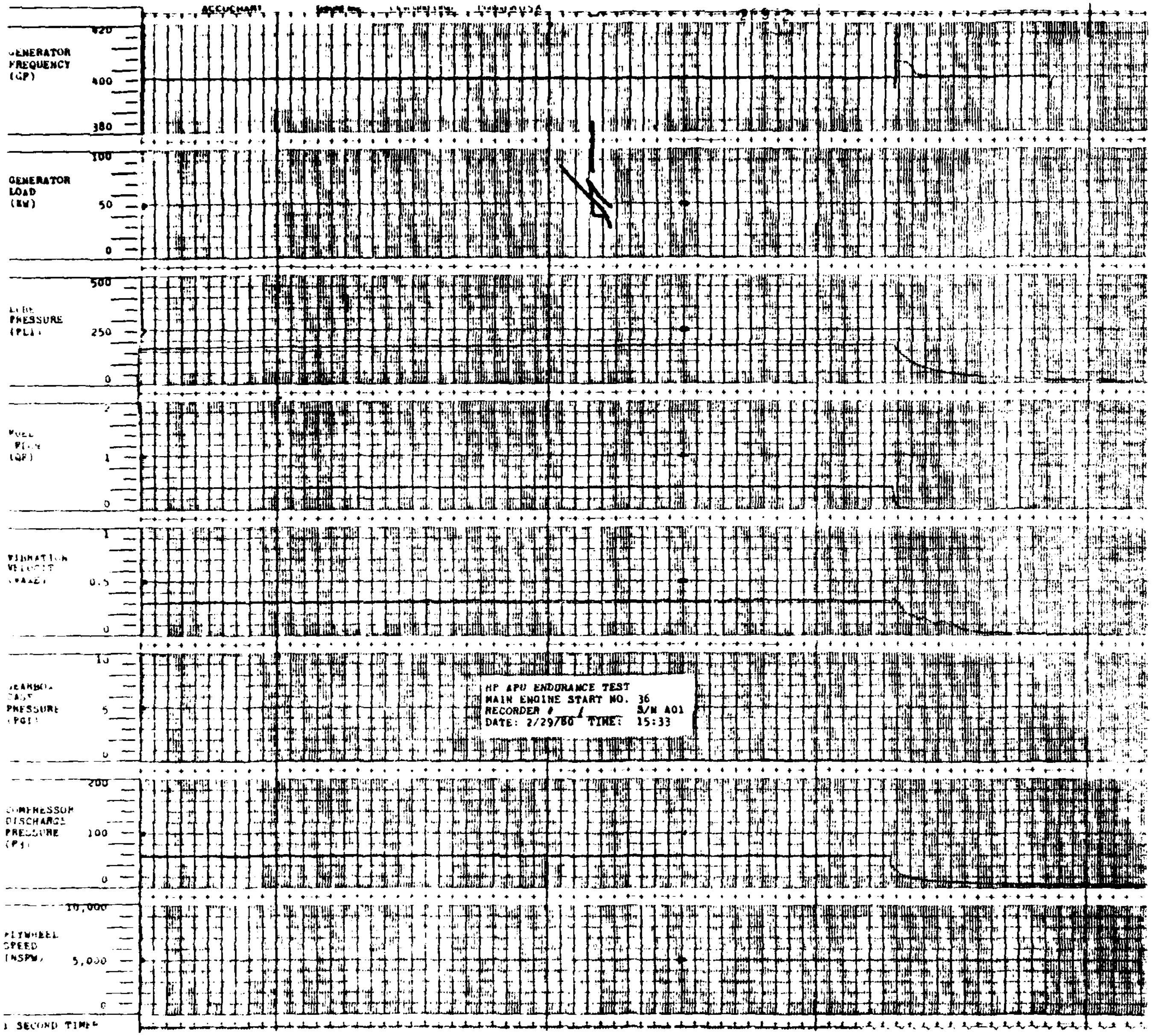

Figure 78. HPAPU Endurance Test (Sheet 7 of 15).

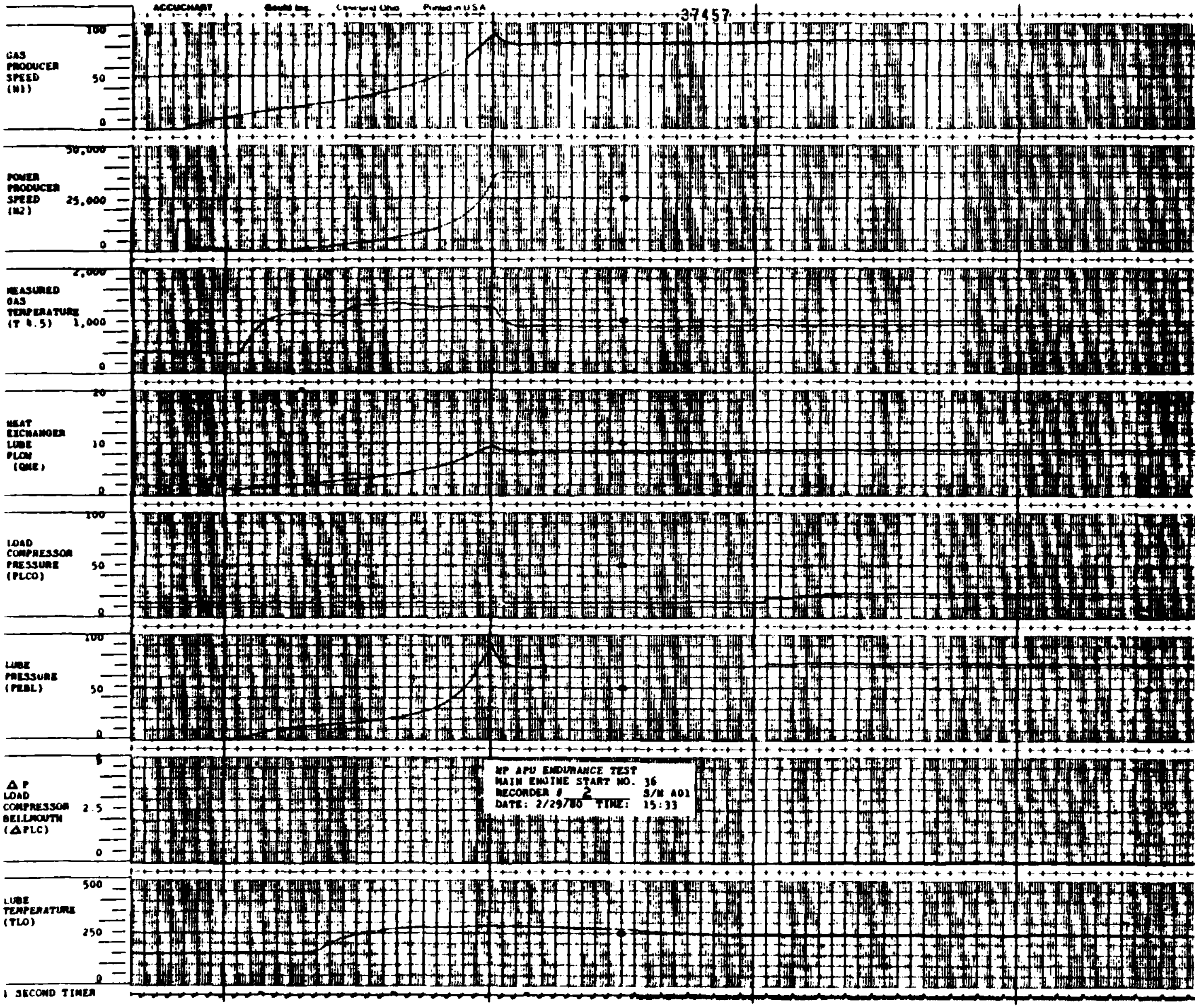

Figure 78. HPAPU Endurance Test (Sheet 8 of 15).

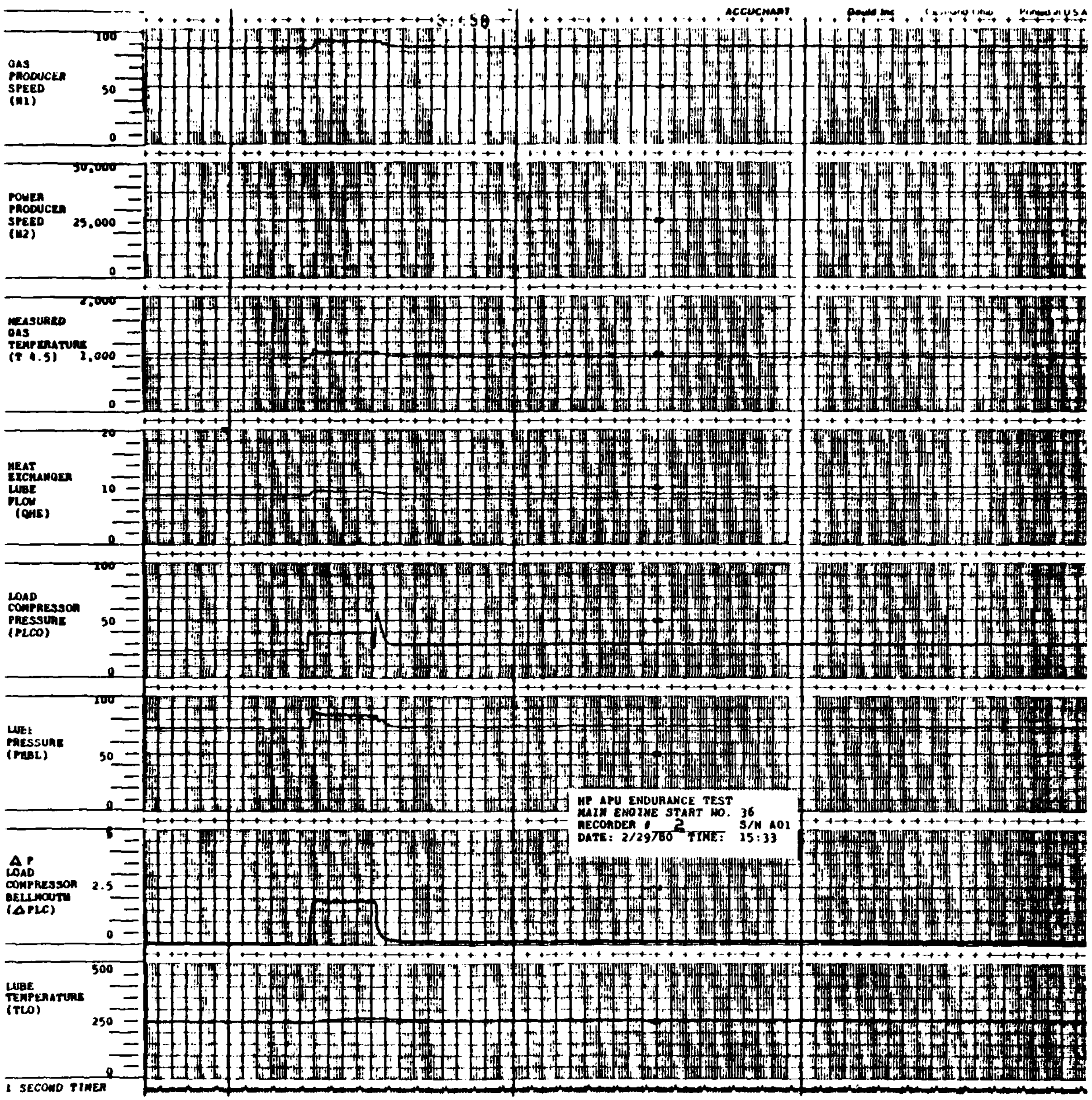

Figure 78. HPAPU Endurance Test (Sheet 9 of 15).

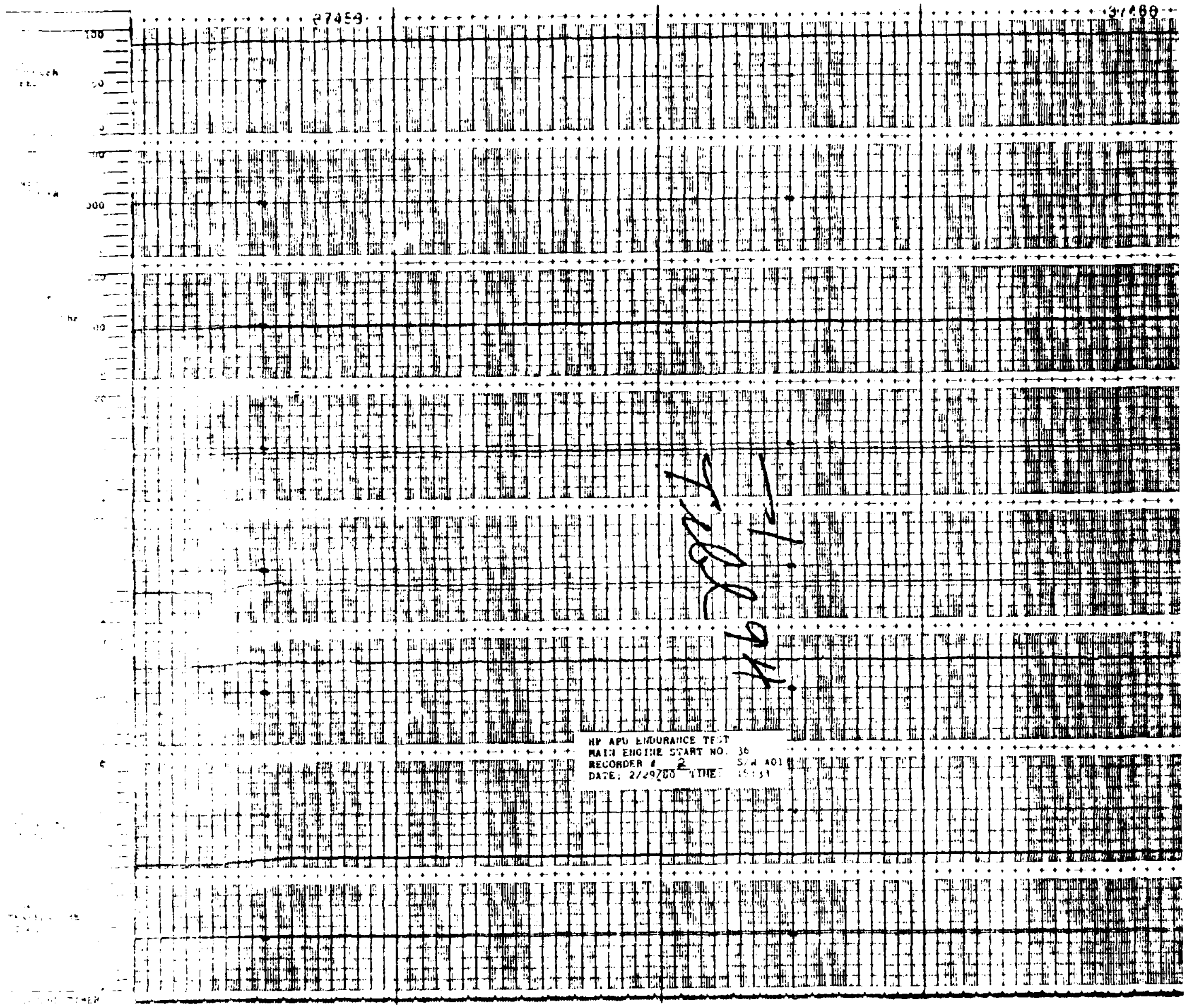

Figure 78. HPAPU Endurance Test (Sheet 10 of 15).

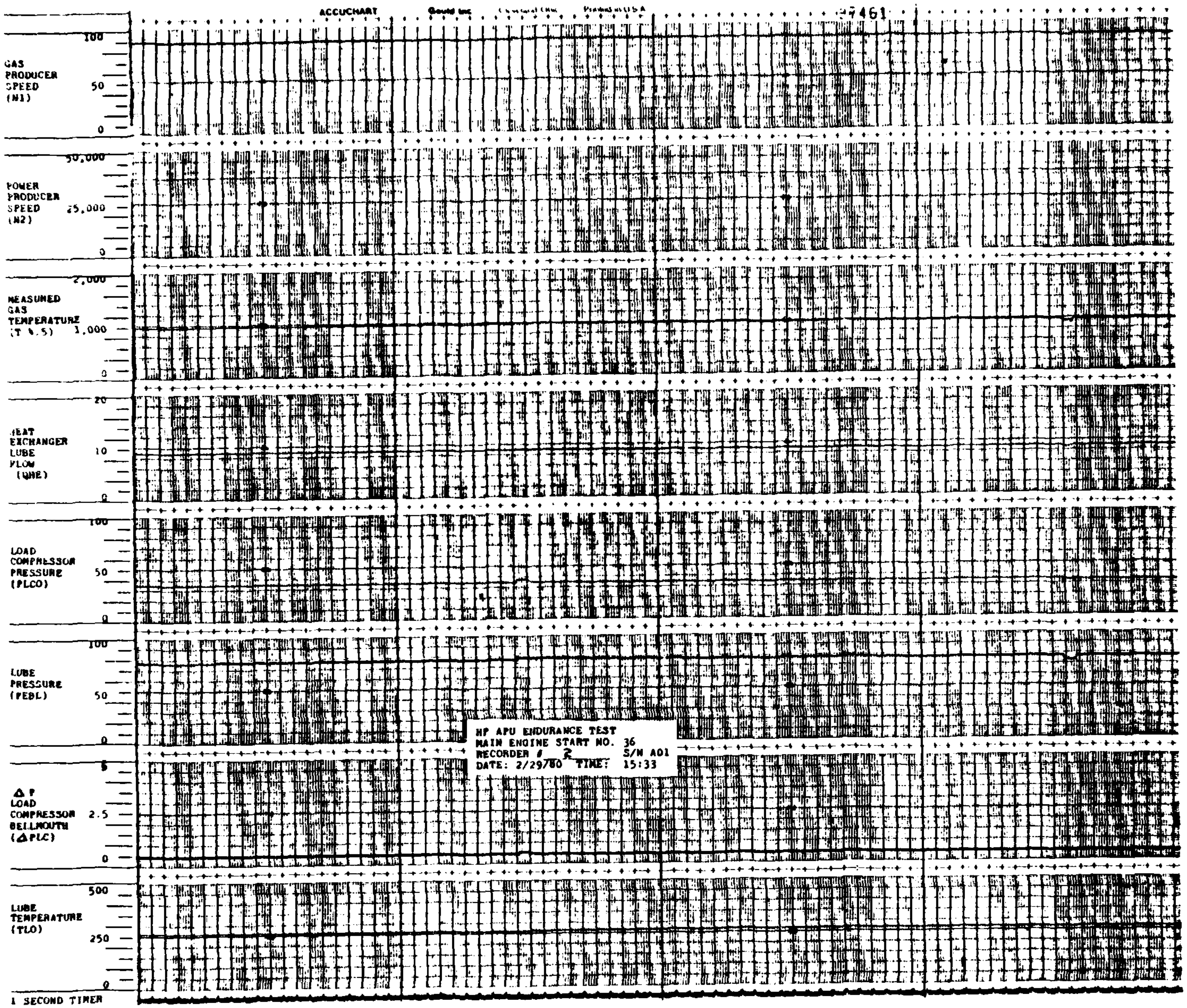

Figure 78. HPAPU Endurance Test (Sheet 11 of 15).

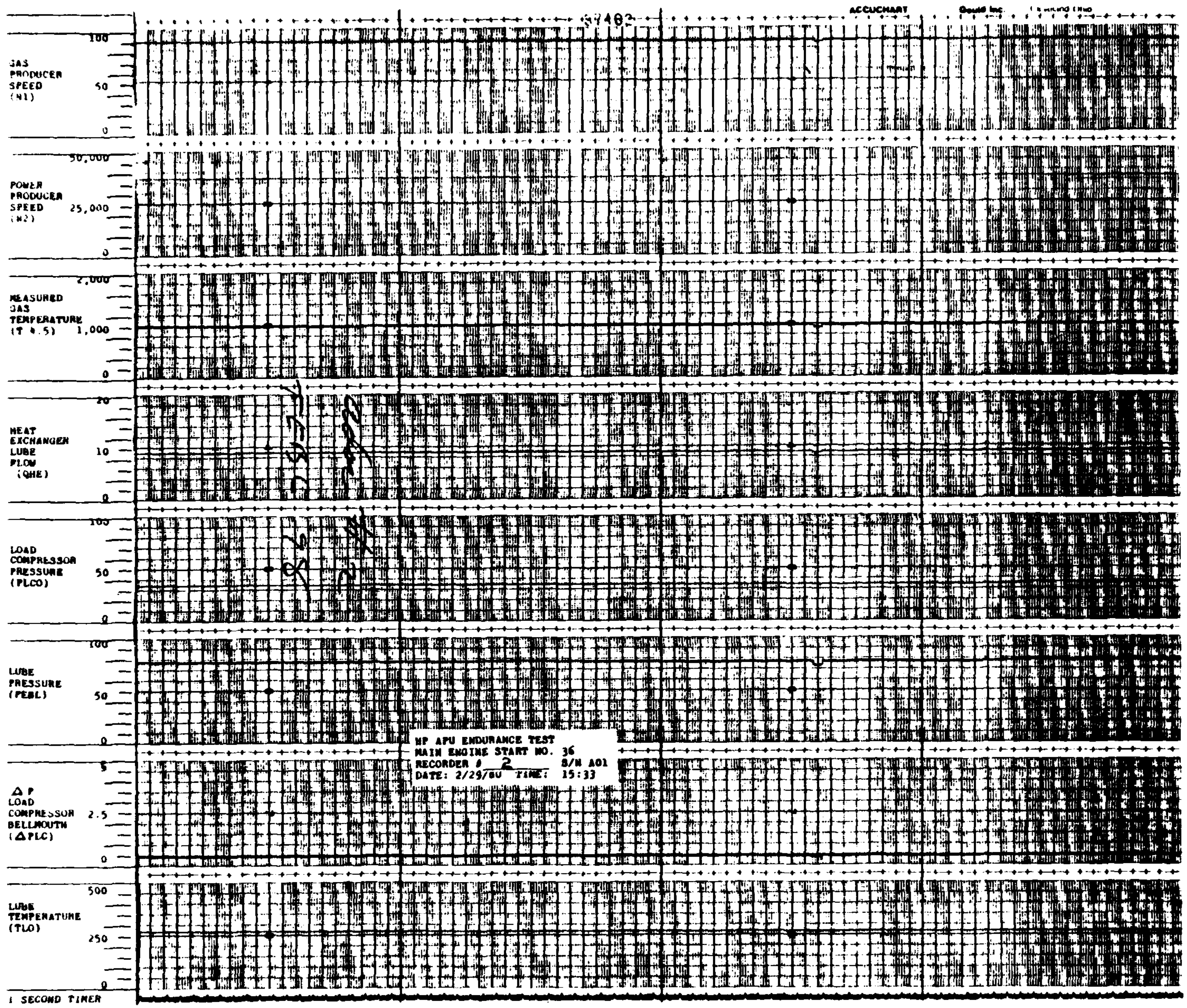

Figure 78. HPAPU Endurance Test (Sheet 12 of 15).

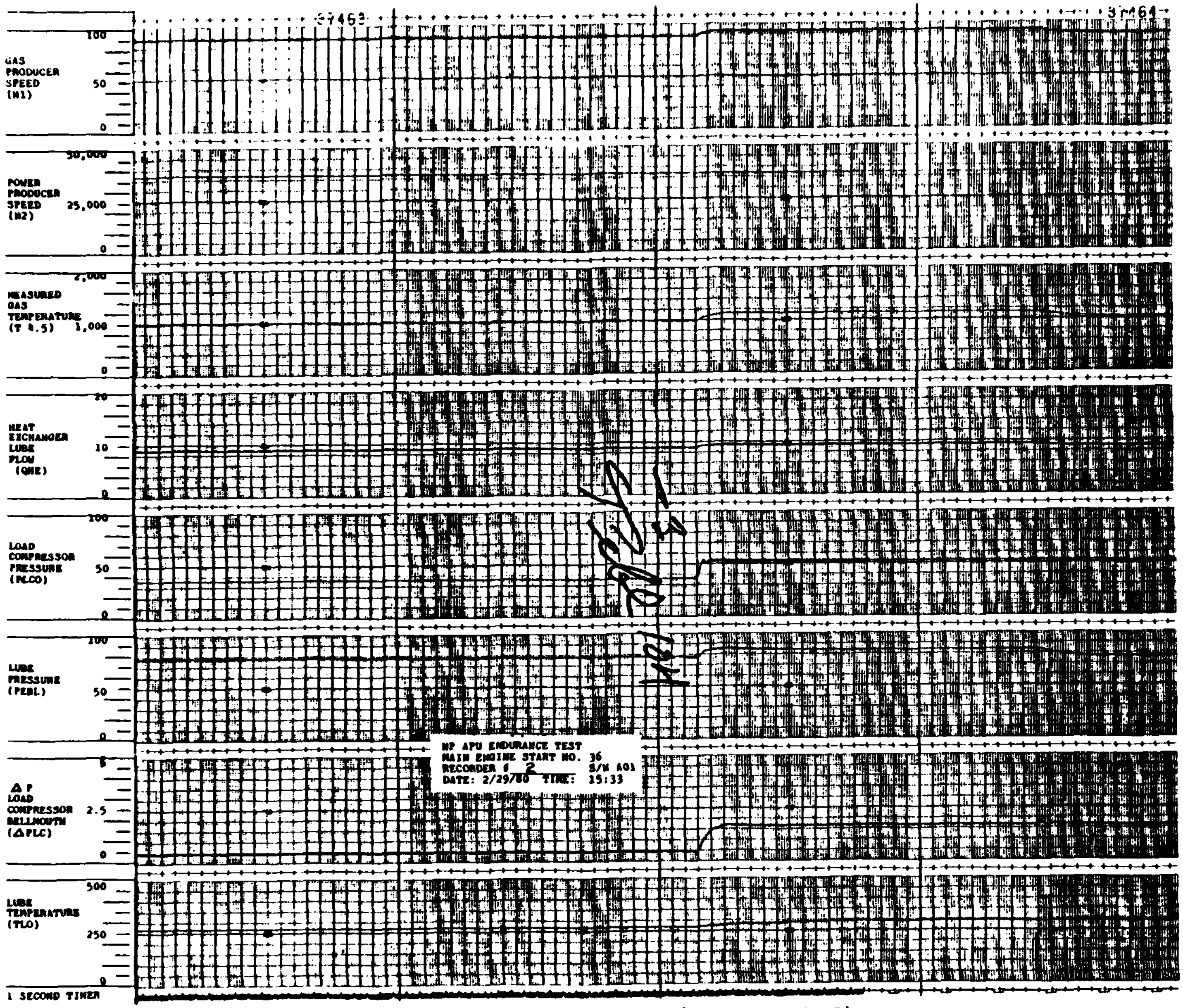

Figure 78. HPAPU Endurance Test (Sheet 13 of 15).

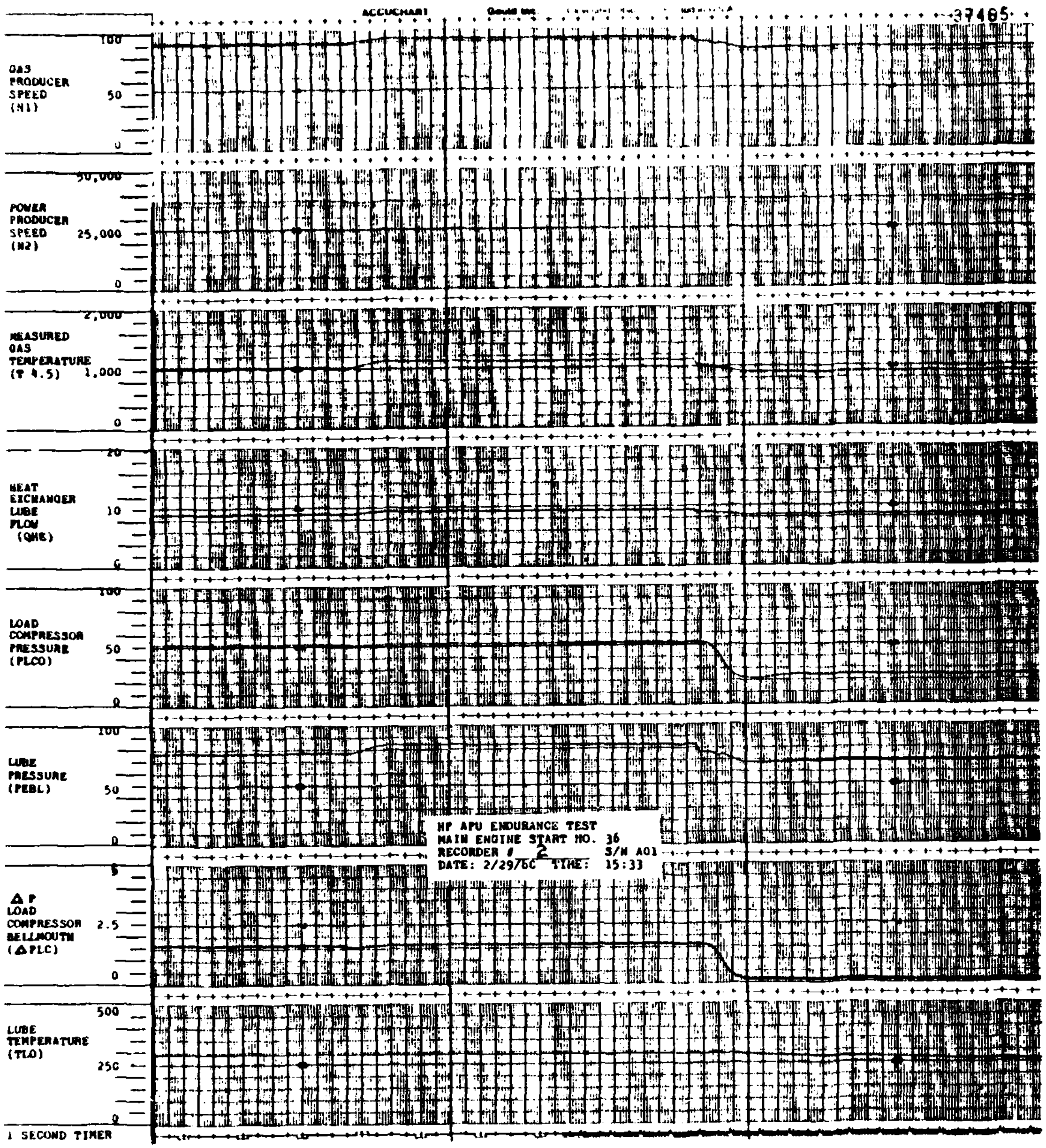

Figure 78. HPAPU Endurance Test (Sheet 14 of 15).

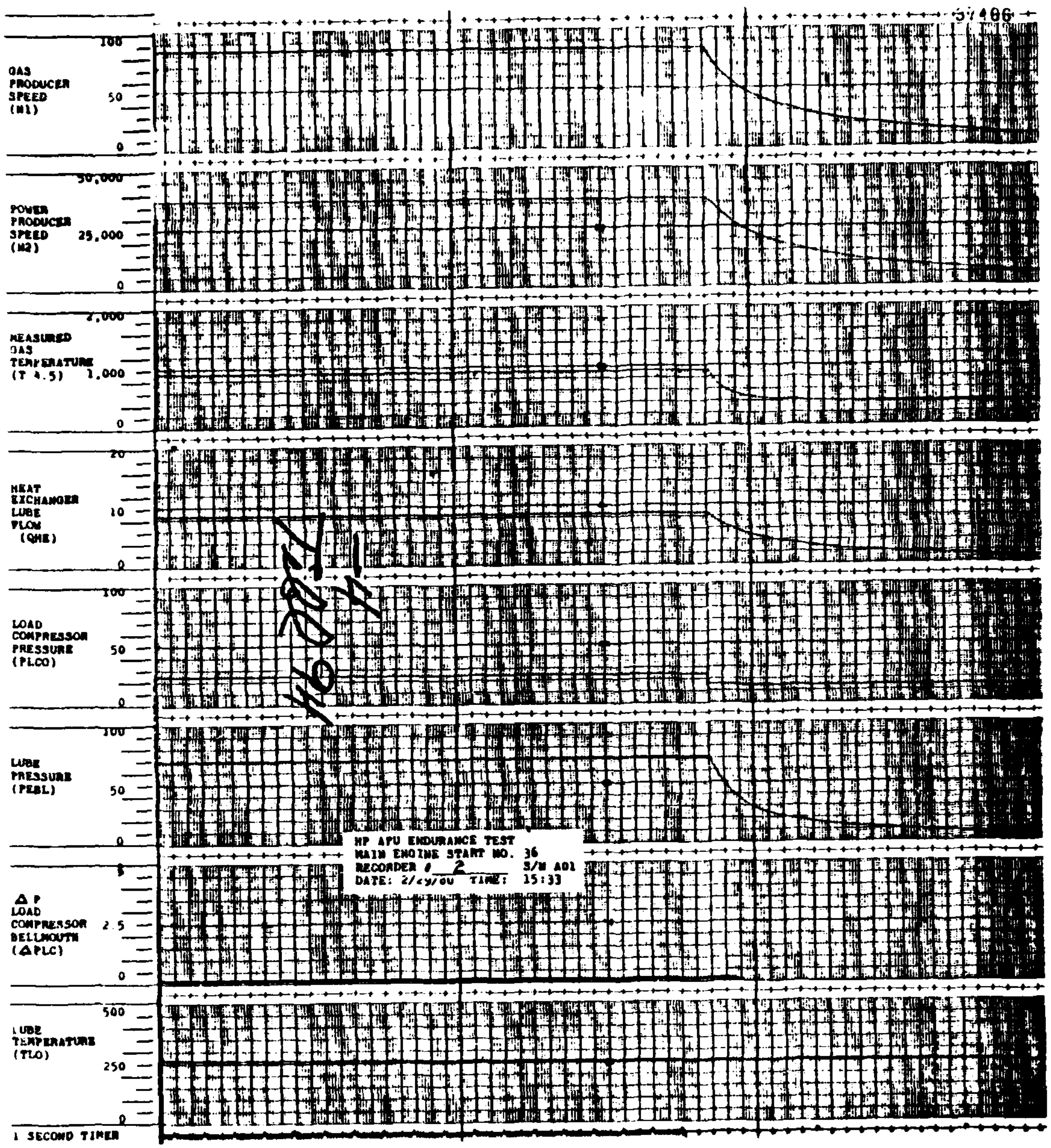

Figure 78. HPAPU Endurance Test (Sheet 15 of 15).

TABLE 19. HPAPU ADAS DATA (SHEET 1 OF 7)

ADAS Acronym Key

1.0 Input Data

The following data entries identify data resulting directly from instrumentation outputs.

1.1	PFI	-	Fuel supply pressure
1.2	PEI	-	Pressure at the engine air inlet
1.3	VS	-	Start motor voltage
1.4	IS	-	Start motor current
1.5	KW	-	Generator load
1.6	PLI	-	Lube system pressure
1.7	PLJ	-	Lube pressure
1.8	PGBI	-	Lube pressure
1.9	PGBJ	-	Lube pressure
1.10	PGBB	-	Lube pressure
1.11	PGI	-	Gearbox pressure
1.12	PEBL	-	Lube pressure to aft bearings
1.13	P3	-	Power producer CDP
1.14	DPHE	-	Lube pressure drop at heat exchanger
1.15	POFP	-	Load airflow orifice pressure
1.16	DPOFP	-	Load airflow orifice P
1.17	N1	-	Gas Generator speed
1.18	N2-1	-	Power Turbine speed
1.19	NSATM	-	Air Turbine Starter speed
1.20	NSFW	-	Flywheel speed
1.21	QF	-	Fuel flow
1.22	QEBL	-	Oil flow to aft bearings

TABLE 19. HPAPU ADAS DATA (SHEET 2 OF 7)

ADAS Acronym Key (Cont)

1.23	QHE	-	System oil flow
1.24	TFI	-	Fuel temperature
1.25	TECI	-	Air temperature at inlet bellmouth
1.26	TLCI	-	Air temperature at load compressor inlet
1.27	TA	-	Cell ambient temperature
1.28	THEOO	-	Oil temperature
1.29	THEOI	-	Oil temperature
1.30	TLO	-	Oil temperature
1.31	TLCO	-	Air temperature at load compressor discharge
1.32	TOFP	-	Air temperature at airflow orifice
1.33	T4.5	-	Power producer operating gas temperature
1.34	DPLC	-	Load compressor inlet P
1.35	PLCI	-	Load compressor inlet pressure
1.36	PLCO	-	Load compressor discharge pressure
1.37	IGVA	-	Inlet guide vane position
1.38	SVP	-	Surge valve position
1.39	GF	-	Generator Frequency
1.40	DEPCI	-	Inlet bellmouth P
1.41 through 1.45		-	Vibration levels

2.0 Output Data

The following entries identify values calculated from the input data as part of the data reduction process.

2.1	SHPLC	-	Load compressor shaft horsepower
2.2	SHPGEN	-	Generator shaft horsepower
2.3	WAEC	-	Power producer air flowrate

TABLE 19. HPAPU ADAS DATA (SHEET 3 OF 7)

ADAS Acronym Key (Cont)

2.4	WF	-	Fuel flowrate
2.5	WFC	-	Corrected fuel flowrate
2.6	T4.5C	-	Corrected gas temperature
2.7	NG	-	Gas generator speed
2.8	NGC	-	Corrected gas generator speed
2.9	NSPT	-	Power turbine speed
2.10	NSPTC	-	Corrected power turbine speed
2.11	PREC	-	Power producer compressor pressure ratio
2.12	WALCC	-	Corrected load compressor air flow
2.13	WALCI	-	Load compressor air flow
2.14	WALCO	-	Air flow at load valve
2.15	WALCS	-	Air flow at surge valve
2.16	NSLC	-	Load compressor speed
2.17	NSLCC	-	Corrected load compressor speed
2.18	PRLC	-	Load compressor pressure ratio
2.19	ELC	-	Load compressor efficiency
2.20	WATM	-	Air flow at air turbine starter
2.21	SHPE	-	Shaft horsepower at the power turbine
2.22	SHPEC	-	Shaft horsepower, corrected
2.23	PBAR	-	Atmospheric pressure
2.24	PBAR	-	Atmospheric pressure

NOTE: Units of each parameter are printed on the data sheets.

TABLE 19. HPAPU ADAS DATA (SHEET 4 OF 7)

HPAPU DATA REDUCTION

TEST CELL 07A   RUN 123(36)   S/N 01   DATE [illegible]/29/80

DATA POINT 1   TIME OF DAY 14:36:49

INPUT DATA

PFI -PSIG	PEI -PSIA	VS -VDC	IS -AMPS	KW -KW
17.4667	14.6365	25.1632	-1.6298	11.2301
PLI -PSIG	PLJ -PSIG	PGBI -PSIG	PGBJ -PSIG	PGBB -PSIG
189.9920	28.2445	82.9410	29.9227	140.2760
PGI -PSIG	PEBL -PSIG	P3 -PSIG	DPHE -PSID	POFP -PSIG
0.0231	77.3478	65.6414	18.4853	19.5074
DPOFP -PSID	N1 -%	N2-1 -RPM	NSATM -RPM	NSFN -RPM
3.6777	86.9771	37062.3000	-6.0402	-4.6342
QF -GPM	QEBL -GPM	QHE -GPM	TFI -DEGF	TECI -DEGF
0.4887	0.5859	8.9143	33.5026	32.1016
TLCI -DEGF	TA -DEGF	THEOO -DEGF	THEOI -DEGF	TLO -DEGF
23.0729	31.2552	154.3660	196.7850	262.1920
TLCO -DEGF	TOFP -DEGF	T4.5 -DEGF	DPLC -PSID	PLCI -PSIA
263.6660	263.8230	984.2410	0.5182	14.9659
PLCO -PSIA	IGVA -DEG	SVP -DEG	GF -HZ	DPECI -"H2O
35.0215	60.0140	70.8026	399.2320	5.3899
VECR -%	VECA -%	VLCR -%	VGH -%	VGV -%
3.5793	8.1266	1.3575	4.9126	6.1022

OUTPUT DATA

SHPLC -HP	SHPGEN -HP	WAEC -LB/S	WF -LB/H	WFC -LB/H
184.8280	23.5845	3.5879	191.9740	201.4130
T4.5C-DEGF	NG -RPM	NGC -RPM	NSPT -RPM	NSPTC -RPM
1065.0000	41633.3000	42756.7000	37062.3000	38061.8000
PREC	WALCC-LB/M	WALCI-LB/M	WALCO-LB/M	WALCS-LB/M
5.4848	122.3500	129.1120	104.6250	24.4872
NSLC -RPM	NSLCC -RPM	PRLC	ELC -%	WATM -LB/S
46906.1000	48619.1000	2.3401	55.2030	0.0000
SHPE -HP	SHPEC -HP	PBAR -"HG	PBAR -PSIA	
249.7070	260.2470	29.6198	14.5519	

TABLE 19. HPAPU ADAS DATA (SHEET 5 OF 7)

HPAPU DATA REDUCTION

TEST CELL 07A   RUN 123(36)   S/N 01   DATE 2/29/80

DATA POINT 2   TIME OF DAY 14:58:11

INPUT DATA

PFI -PSIG 17.4210	PEI -PSIA 14.6367	VS -VDC 25.2027	IS -AMPS -1.4632	KW -KW 49.9136
PLI -PSIG 188.9960	PLJ -PSIG 28.0250	PGBI -PSIG 83.3505	PGBJ -PSIG 29.8613	PGBB -PSIG 139.7680
PGI -PSIG 0.0100	PEBL -PSIG 77.9199	P3 -PSIG 72.4863	DPHE -PSID 17.3325	POFP -PSIG 13.4122
DPOFP -PSID 3.5486	N1 -% 87.7379	N2-1 -RPM 37070.9000	NSATM -RPM -6.3526	NSFW -RPM -5.0508
QF -GPM 0.5341	QEBL -GPM 0.5974	QHE -GPM 8.9240	TFI -DEGF 32.1250	TECI -DEGF 27.2031
TLCI -DEGF 21.3984	TA -DEGF 28.2996	THEOO -DEGF 161.4040	THEOI -DEGF 207.6090	TLO -DEGF 270.1740
TLCO -DEGF 262.5490	TOFP -DEGF 262.4370	T4.5 -DEGF 995.5720	DPLC -PSID 0.5000	PLCI -PSIA 14.9860
PLCO -PSIA 34.9469	IGVA -DEG 60.6497	SVP -DEG 71.4709	GF -HZ 399.3470	DPECI -"H2O 6.2760
VECR -% 2.4963	VECA -% 8.0870	VLCR -% 1.3512	VGH -% 4.9418	VGV -% 6.4223

OUTPUT DATA

SHPLC -HP 182.5810	SHPGEN -HP 75.6173	WAEC -LB/S 3.8667	WF -LB/H 209.9440	WFC -LB/H 221.8420
T4.5C-DEGF 1092.7600	NG -RPM 41997.5000	NGC -RPM 43347.1000	NSPT -RPM 37070.9000	NSPTC -RPM 38261.5000
PREC 5.9524	WALCC-LB/M 120.2130	WALCI-LB/M 127.2480	WALCO-LB/M 102.8650	WALCS-LB/M 24.3830
NSLC -RPM 46917.0000	NSLCC -RPM 48714.8000	PRLC 2.3320	ELC -% 54.6321	WATM -LB/S 0.0000
SHPE -HP 301.2360	SHPEC -HP 315.8010	PBAR -"HG 29.6198	PBAR -PSIA 14.5519	

TABLE 19. HPAPU ADAS DATA (SHEET 6 OF 7)

HPAPU DATA REDUCTION

TEST CELL 07A RUN 123(36) S/N 01 DATE 2/29/80

DATA POINT 3 TIME OF DAY 15:16: 5

INPUT DATA

PFI -PSIG	PEI -PSIA	VS -VDC	IS -AMPS	KW -KW
16.9078	14.6363	25.2169	-1.5152	74.3536
PLI -PSIG	PLJ -PSIG	PGBI -PSIG	PGBJ -PSIG	PGBB -PSIG
204.0930	30.3223	92.3019	38.0449	152.6240
PGI -PSIG	PEBL -PSIG	P3 -PSIG	DPHE -PSID	POFP -PSIG
0.1405	85.0715	93.6297	17.2224	37.4589
DPOFP -PSID	N1 -%	N2-1 -RPM	NSATM -RPM	NSFW -RPM
7.8671	92.8111	37053.5000	-6.7171	-4.9467
QF -GPM	QEBL -GPM	QHE -GPM	TFI -DEGF	TECI -DEGF
0.7396	0.6493	9.3649	31.3151	28.0677
TLCI -DEGF	TA -DEGF	THEOO -DEGF	THEOI -DEGF	TLO -DEGF
21.5417	28.2501	170.4290	212.7860	289.1280
TLCO -DEGF	TOFP -DEGF	T4.5 -DEGF	DPLC -PSID	PLCI -PSIA
309.0990	309.4320	1141.5300	1.7282	14.6606
PLCO -PSIA	IGVA -DEG	SVP -DEG	GF -HZ	DPECI -"H2O
53.0703	-4.5974	71.9533	399.1810	8.8543
VECR -%	VECA -%	VLCR -%	VGH -%	VGV -%
2.7415	8.8176	1.5746	5.0865	6.4827

OUTPUT DATA

SHPLC -HP	SHPGEN -HP	WAEC -LB/S	WF -LB/H	WFC -LB/H
376.0850	111.7770	4.5759	290.8730	306.9700
T4.5C-DEGF	NG -RPM	NGC -RPM	NSPT -RPM	NSPTC -RPM
1245.3800	44425.9000	45812.9000	37053.5000	38209.6000
PREC	WALCC-LB/M	WALCI-LB/M	WALCO-LB/M	WALCS-LB/M
7.3971	212.2970	219.8090	180.2520	39.5573
NSLC -RPM	NSLCC -RPM	PRLC	ELC -%	WATM -LB/S
46894.9000	48684.6000	3.6199	74.3811	0.0000
SHPE -HP	SHPEC -HP	PBAR -"HG	PBAR -PSIA	
538.9370	564.4070	29.6198	14.5519	

TABLE 19. HPAPU ADAS DATA (SHEET 7 OF 7)

HPAPU DATA REDUCTION

TEST CELL 07A RUN 123(36) S/N 01 DATE 2/29/80

DATA POINT 4 TIME OF DAY 15:21:14

INPUT DATA

PFI -PSIG	PEI -PSIA	VS -VDC	IS -AMPS	KW -KW
17.8056	14.6349	25.2174	-1.3330	-0.0151
PLI -PSIG	PLJ -PSIG	PGBI -PSIG	PGBJ -PSIG	PGBB -PSIG
175.2700	25.8418	76.1706	27.2559	128.5340
PGI -PSIG	PEBL -PSIG	P3 -PSIG	DPHE -PSID	POFP -PSIG
0.0534	70.2539	56.1402	17.0209	9.3984
DPOFP -PSID	N1 -%	N2-1 -RPM	NSATM -RPM	NSFW -RPM
2.1494	83.7874	37068.6000	-6.4046	-4.9987
QF -GPM	QEBL -GPM	QHE -GPM	TFI -DEGF	TECI -DEGF
0.4162	0.5483	8.5601	31.1745	31.3255
TLCI -DEGF	TA -DEGF	THEOO -DEGF	THEOI -DEGF	TLO -DEGF
18.8828	30.1501	157.3700	205.5890	261.1380
TLCO -DEGF	TOFP -DEGF	T4.5 -DEGF	DPLC -PSID	PLCI -PSIA
248.7940	251.8260	929.6460	0.2087	15.0712
PLCO -PSIA	IGVA -DEG	SVP -DEG	GF -HZ	DPECI -"H2O
25.0812	71.2803	71.1903	399.3480	4.3325
VECR -%	VECA -%	VLCR -%	VGH -%	VGV -%
3.5059	8.1235	1.2835	5.8820	5.3057

OUTPUT DATA

SHPLC -HP	SHPGEN -HP	WAEC -LB/S	WF -LB/H	WFC -LB/H
114.6140	9.6544	3.2217	163.7100	171.9530
T4.5C-DEGF	NG -RPM	NGC -RPM	NSPT -RPM	NSPTC -RPM
1009.7200	40106.5000	41221.2000	37068.6000	38098.2000
PREC	WALCC-LB/M	WALCI-LB/M	WALCO-LB/M	WALCS-LB/M
4.8361	78.4985	83.7839	68.1824	15.6015
NSLC -RPM	NSLCC -RPM	PRLC	ELC -%	WATM -LB/S
46914.0000	48839.5000	1.6642	32.6256	0.0000
SHPE -HP	SHPEC -HP	PBAR -"HG	PBAR -PSIA	
162.6180	169.6390	29.6198	14.5519	

Early in the 50-hour full load test a substantial oil leak developed. The source of the leak could not be located during test but in the interest of meeting the intent of the test, the APU was not shut down. Oil was added to the system, as necessary, to maintain a safe level and the 50-hour test was completed. After the test, the cause of the leakage was found to be failure of the sealing adhesive at a plug in the accessory drive gearbox. The plug was incorporated as a modification to the accessory gearbox, to accept the adapter gearbox and LPU101-700 Power Producer. The plug had been assembled to the gearbox housing and sealed with an epoxy adhesive. During endurance testing, the adhesive failed, allowing oil leakage around the plug. Oil consumption during the 50 hours at full load was 37.5 gallons, almost entirely as leakage at the plug. The plug was modified to accept an "O" ring seal and reassembled into the gearbox before endurance Cycle No. 4. The remaining 47 cycles were run with only a single oil addition, and that addition was necessary to make-up oil lost due to an operator error after Cycle No. 42.

Following completion of the 50 endurance cycles and 50 hours of peak power operation, the unit was prepared for the formal demonstration run.

Due to the number of witnessing personnel, the demonstration run was performed twice. Each run included low load operation, 250 and 300 hp operation, peak power operation, generator load transients of 11 KW, 50 KW, and 75 KW, and 2 simulated main engine starts. These runs were completed without incident.

The unit was removed from the test cell and shipped to Avco Lycoming.

At Avco the power producer S/N 202 was disassembled from the HPAPU demonstrator for post test calibration, disassembly, and inspection. As during the pretest calibration test, the power producer was mated to an LTS101-600A2 gearbox and power was absorbed by an LTCT2040 water brake.

Performance

Results of the post endurance test calibration indicate a decrease in power producer performance as a result of the testing at Sundstrand, although it still met HPAPU requirements. The performance shift was the result of a dirty compressor. While installing the HPAPU at Sundstrand the engine ran for some time with engine exhaust gases contaminated with oil, recirculating within the test cell and entering the engine inlet.

The performance degradation was shown at maximum power as a 3 percent increase in specific fuel consumption and an increase in power turbine inlet temperature of 20°F. At 100% gas producer speed, there was a 3% decrease in airflow and a decrease of 16 shaft horsepower. Figures 79 through 82 reflect this performance loss, comparing the post test calibration with that obtained prior to endurance testing. Restored performance was demonstrated on a power producer final assembly with cleaned up hardware.

Inspection

Upon completion of post test calibration, LPU 700, S/N 202, was disassembled. Dimensional, fluorescent penetrant, and magnetic particle inspections were performed as required. The disassembled power producer was reviewed by the contracting agency. Apart from the compressor contamination already discussed, the power producer components were in excellent condition. One blade in the gas producer turbine was replaced because of fluorescent penetrant indications in the ball root. All other parts were suitable, after cleaning, for final reassembly of this power producer.

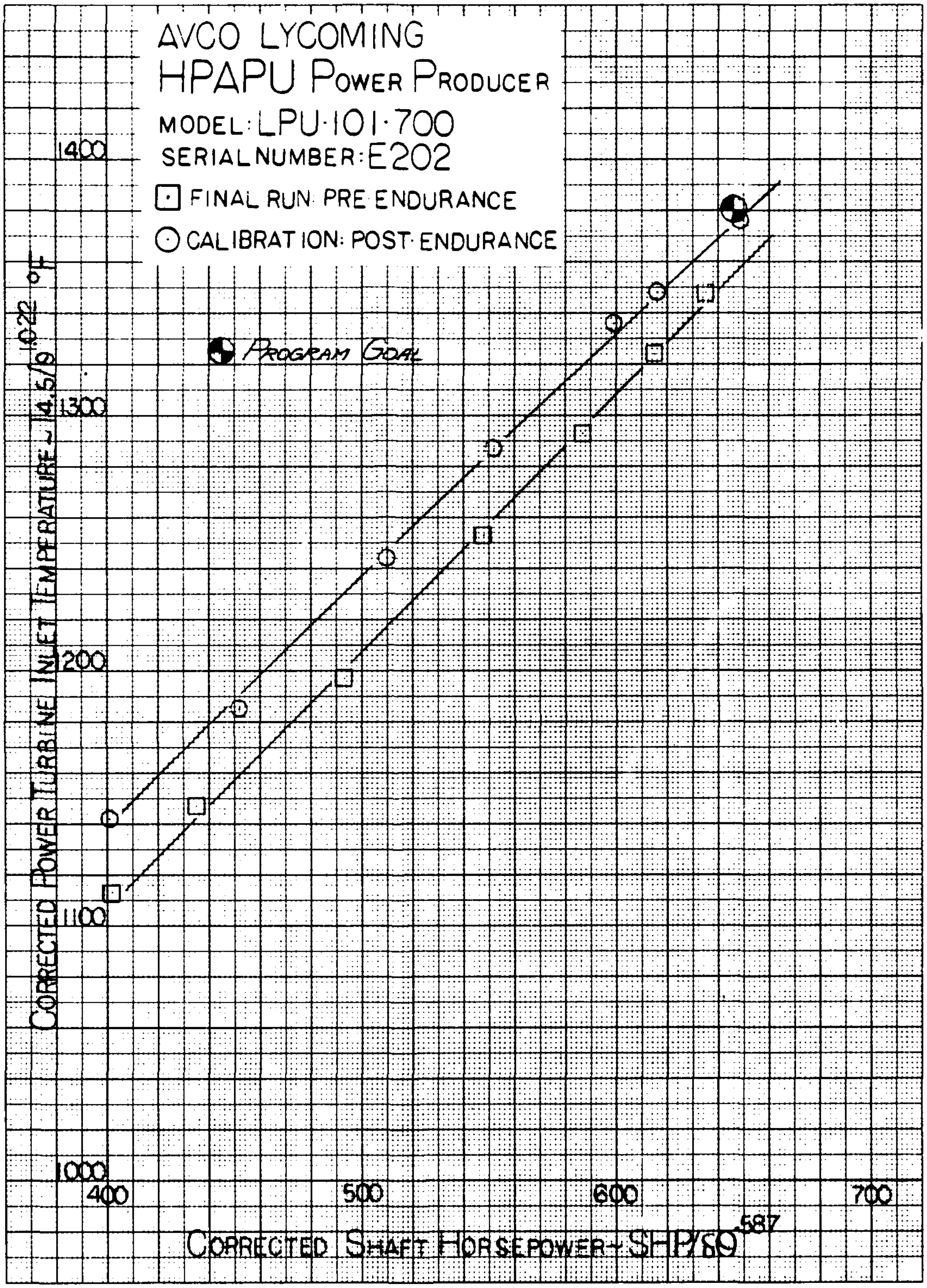

Figure 79. Pre- and Post-Endurance Calibration - Corrected Power Turbine Temperature Versus Corrected Shaft Horsepower

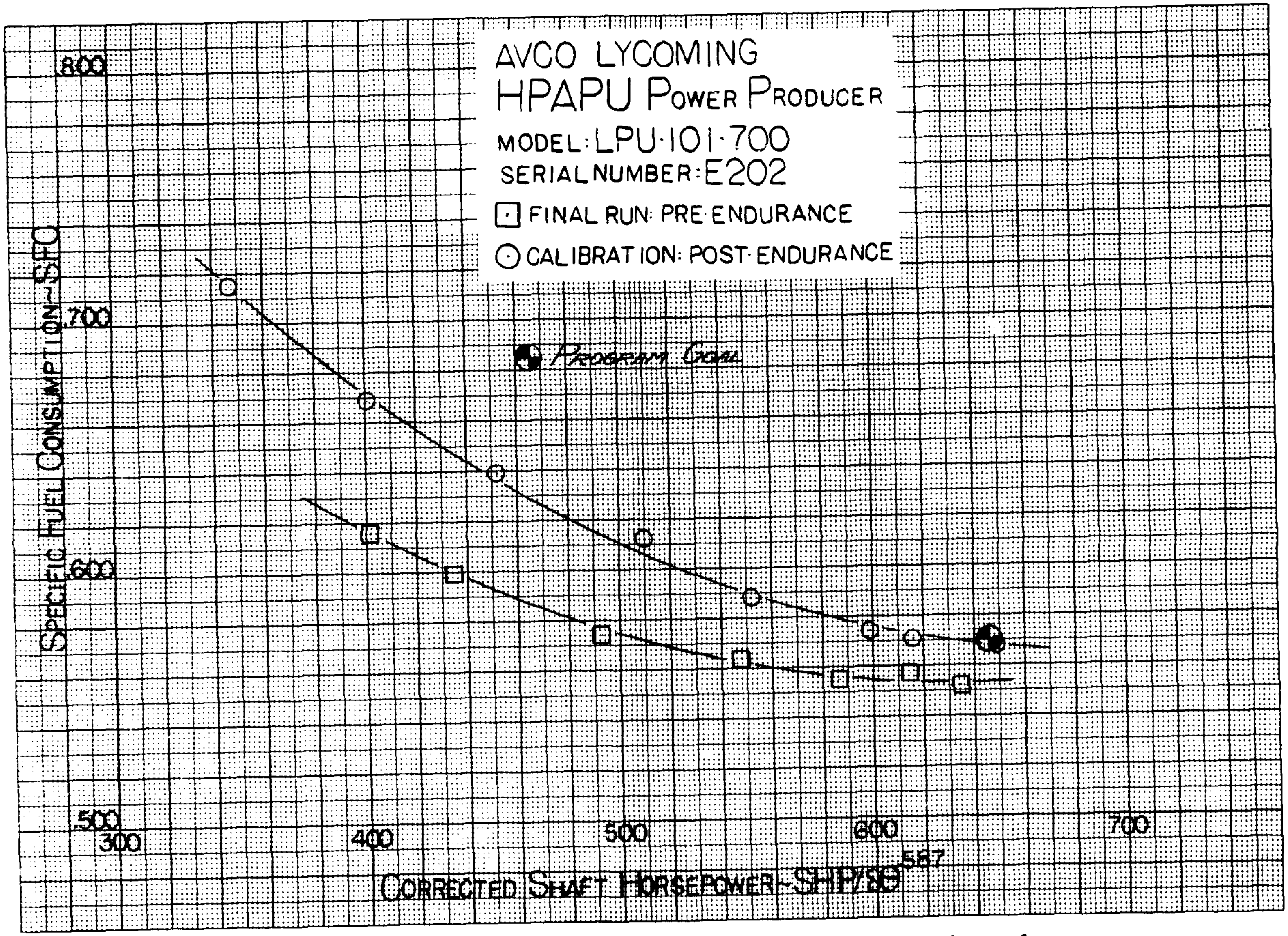

Figure 80. Pre- and Post-Endurance Calibration - Specific Fuel Consumption Versus Corrected Shaft Horsepower

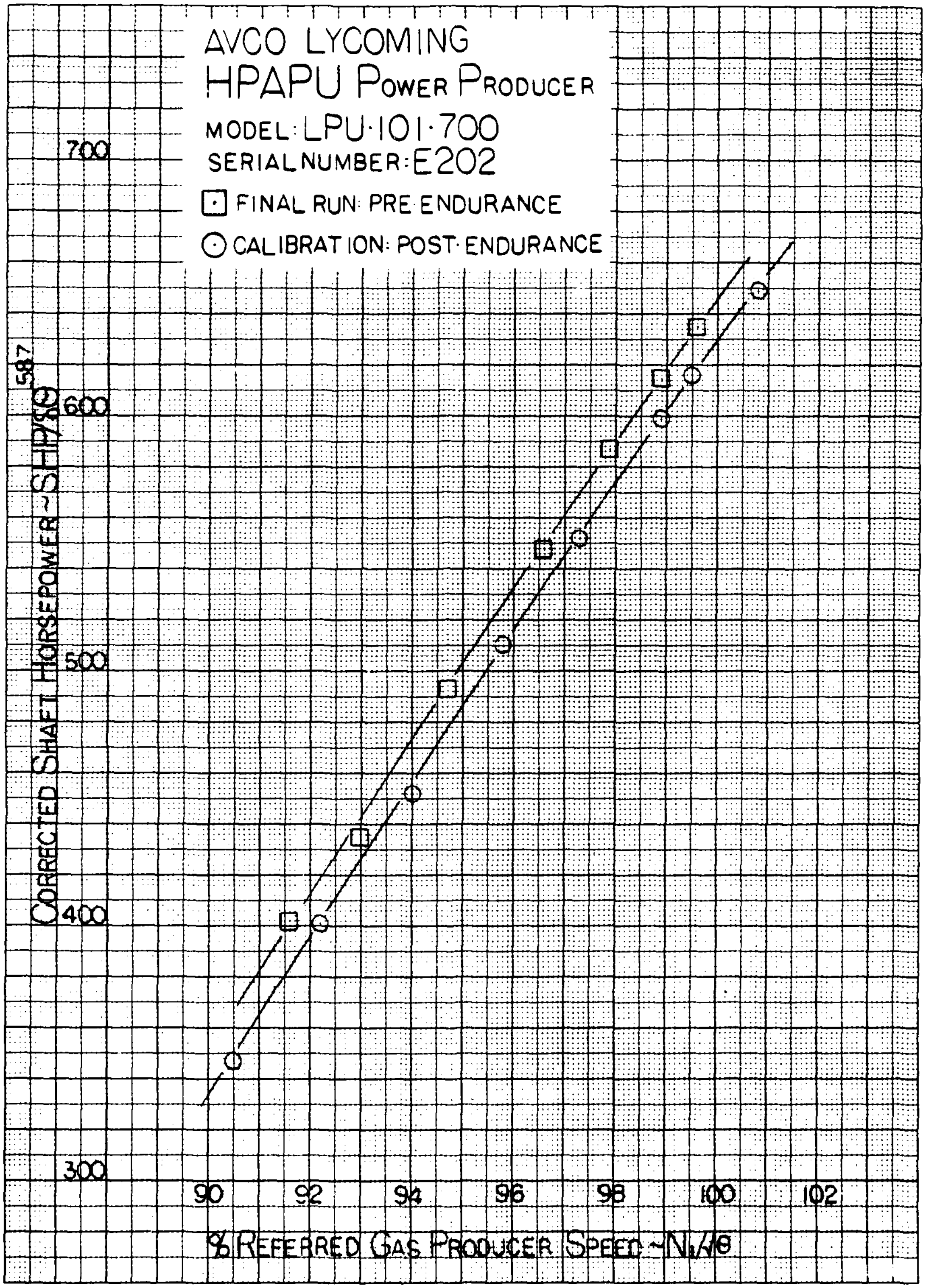

Figure 81. Pre- and Post-Endurance Calibration - Corrected Shaft Horsepower Versus Referred Gas Producer Speed

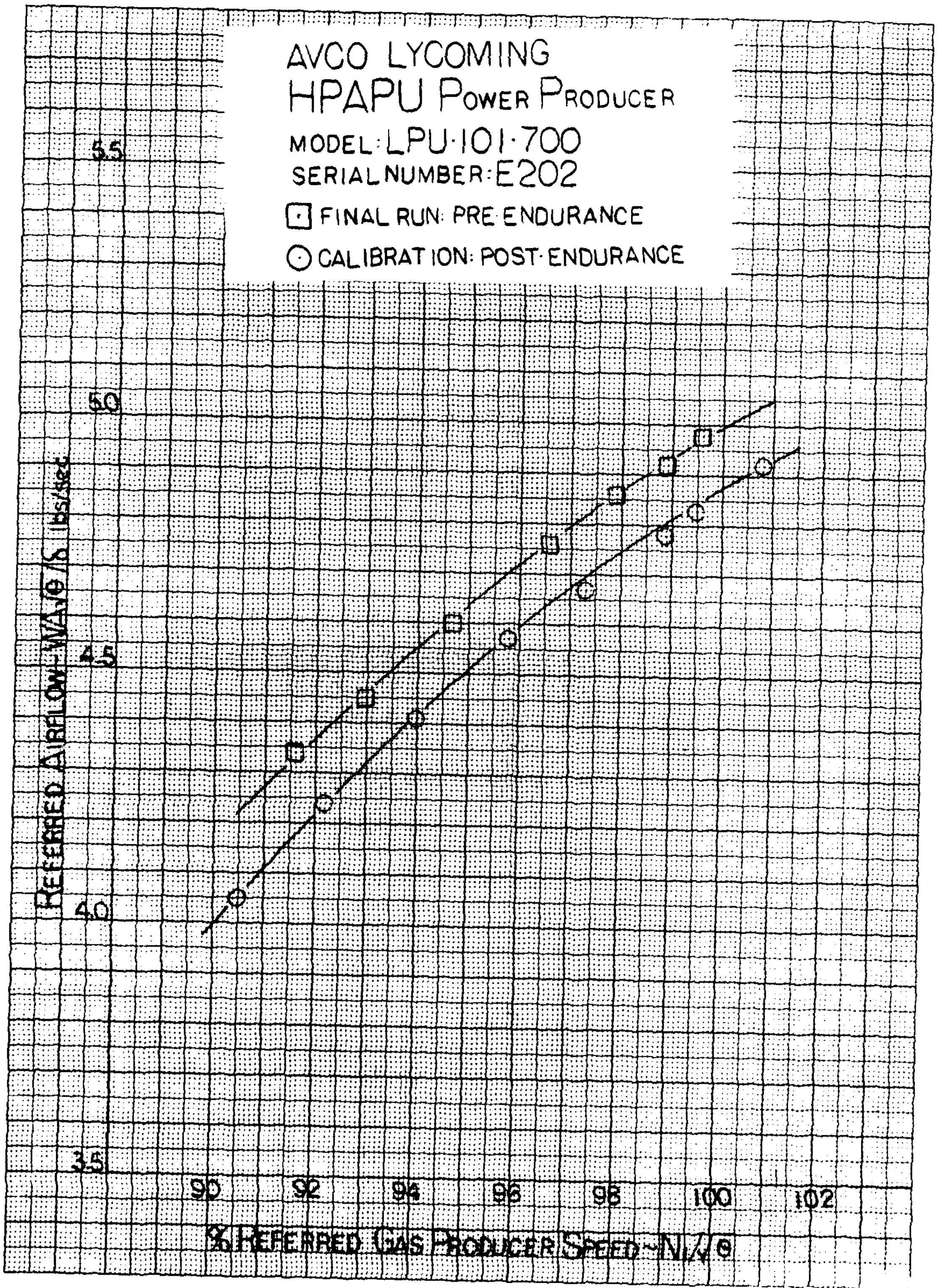

Figure 82. Pre- and Post-Endurance Calibration - Referred Airflow Versus Referred Gas Producer Speed

SECTION IV. HPAPU DELIVERY

4.1 SYSTEM NO. 1

Power producer LPU 700, S/N 201 was reassembled using the folowing new parts:

Ignitor	P/N 1-300-348
Axial Compressor	P/N 4-101-006-21
Diffuser	P/N 4-101-090-08
Diffuser Housing	P/N 4-101-170-08

The power producer was acceptance-tested using, as in previous tests, a standard LTS 101-600A2 gearbox and a Lycoming LTCT2040 water brake. All performance requirements were met or exceeded as shown in Figures 83 through 85.

4.2 SYSTEM NO. 2

Power producer LPU 700, S/N 202, was reassembled using all the original hardware except for one blade, P/N 4-111-014-05, in the gas producer turbine. The unit was acceptance-tested as above and met all performance requirements, as shown in Figures 86 through 88.

LPU 700 power producers, S/N 201 and S/N 202, were installed in their respective HPAPU assemblies in accordance with contractual requirements; both systems were shipped to the Air Force on 24 July 1980.

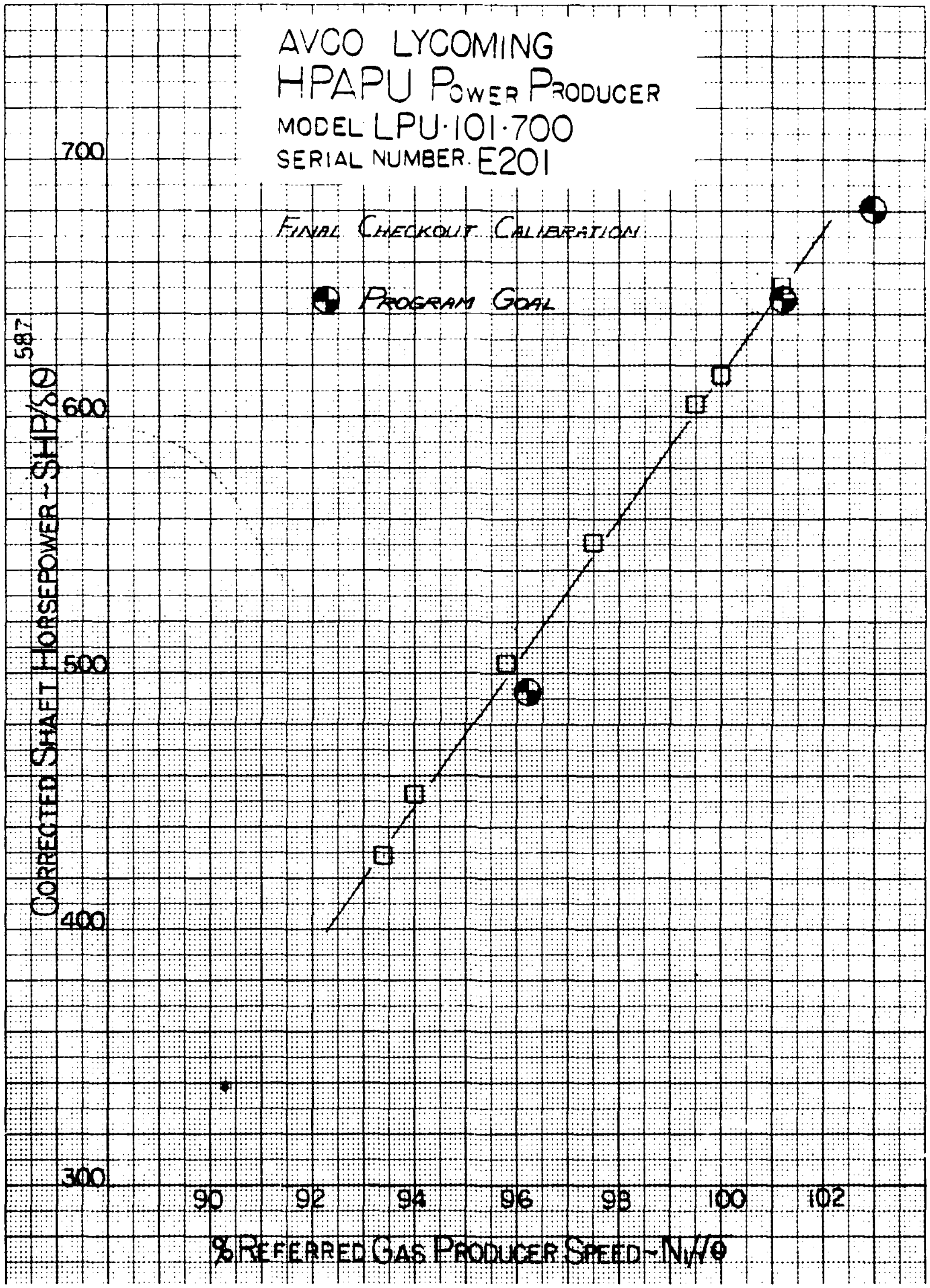

Figure 83. Final Checkout Calibration - Corrected Shaft Horsepower Versus Referred Gas Producer Speed, Engine S/N E201

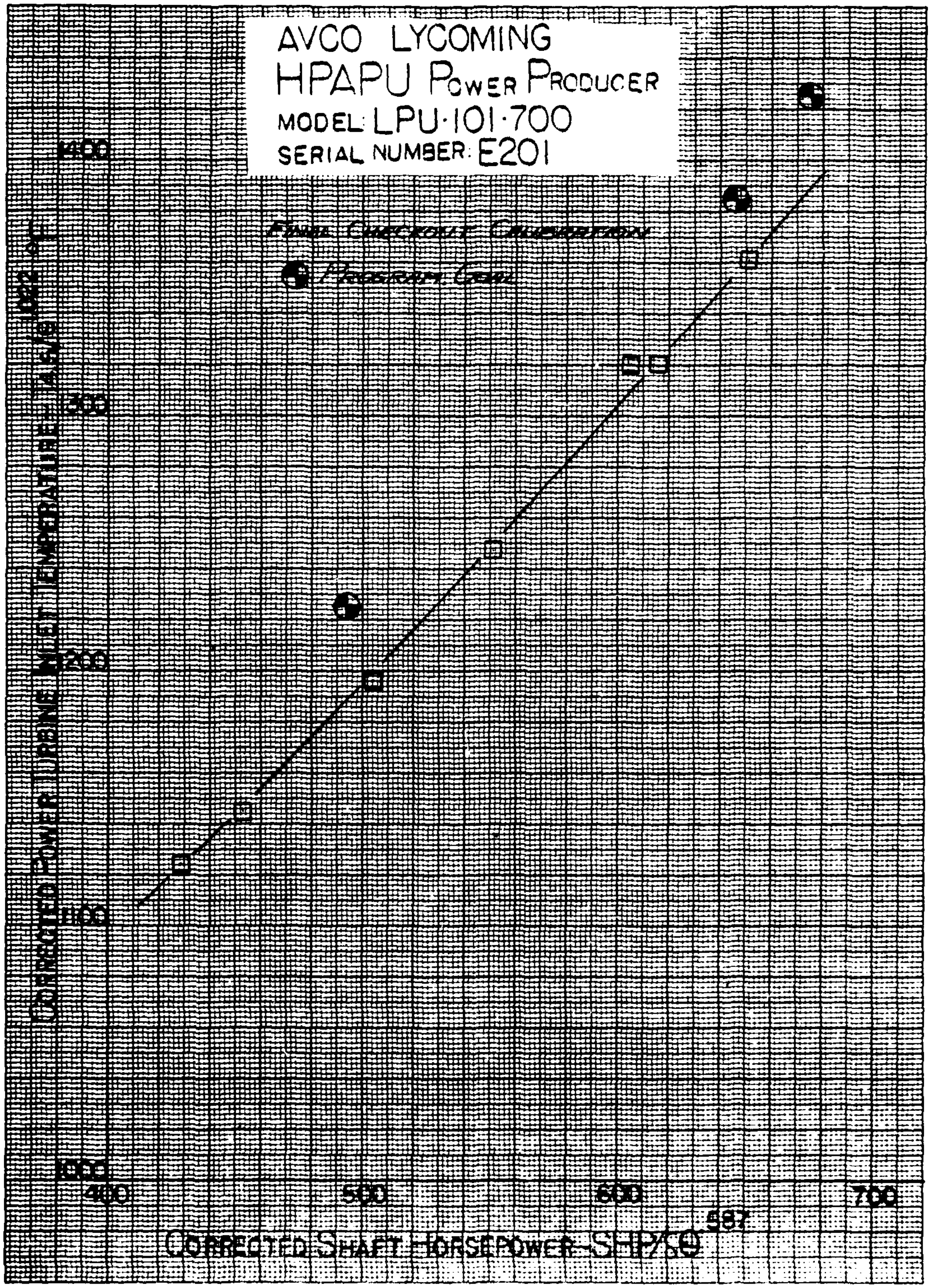

Figure 84. Final Checkout Calibration - Corrected Turbine Inlet Temperature Versus Corrected Shaft Horsepower, Engine S/N E201

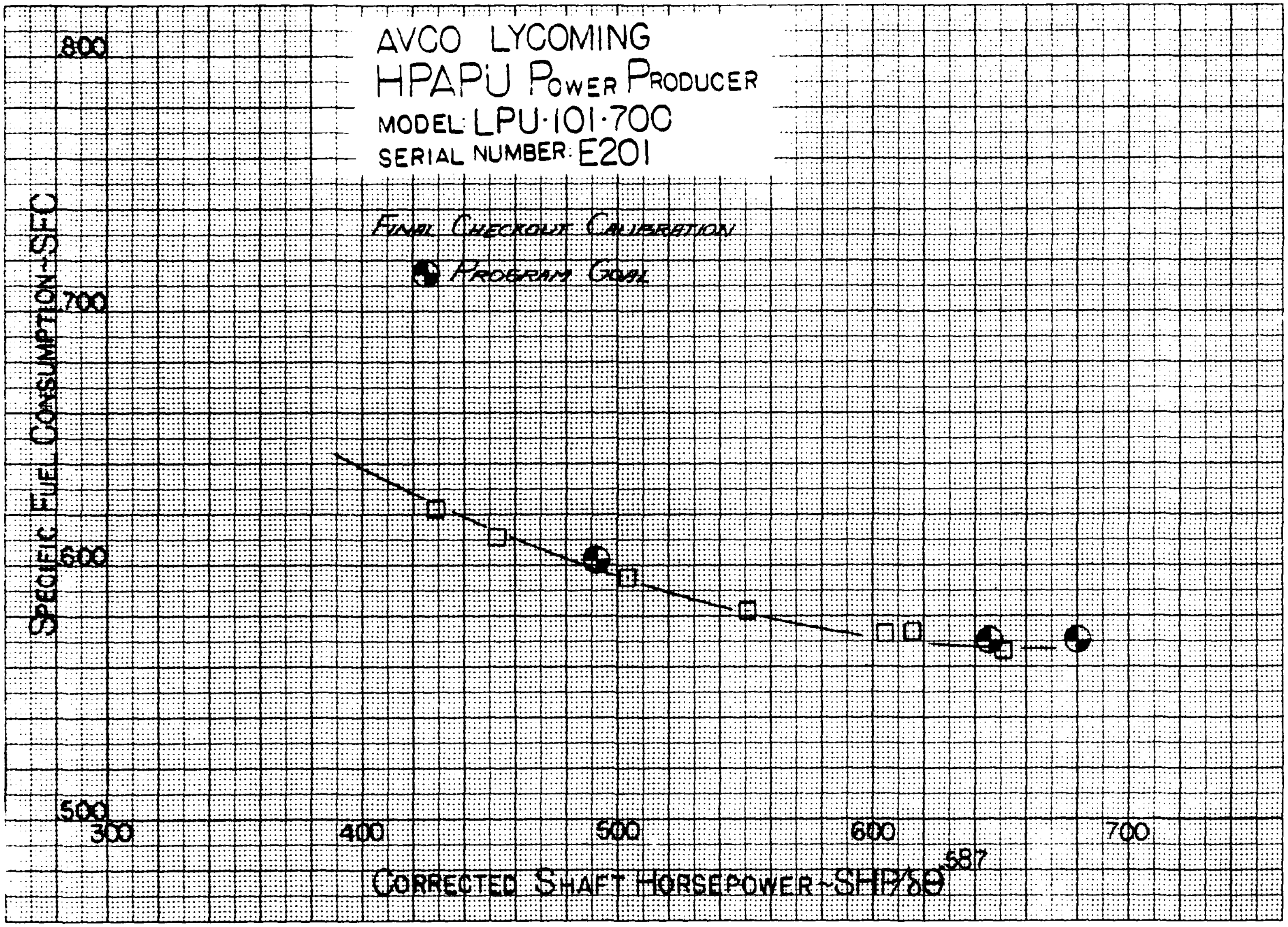

Figure 85. Final Checkout Calibration - Specific Fuel Consumption Versus Corrected Shaft Horsepower, Engine S/N E201

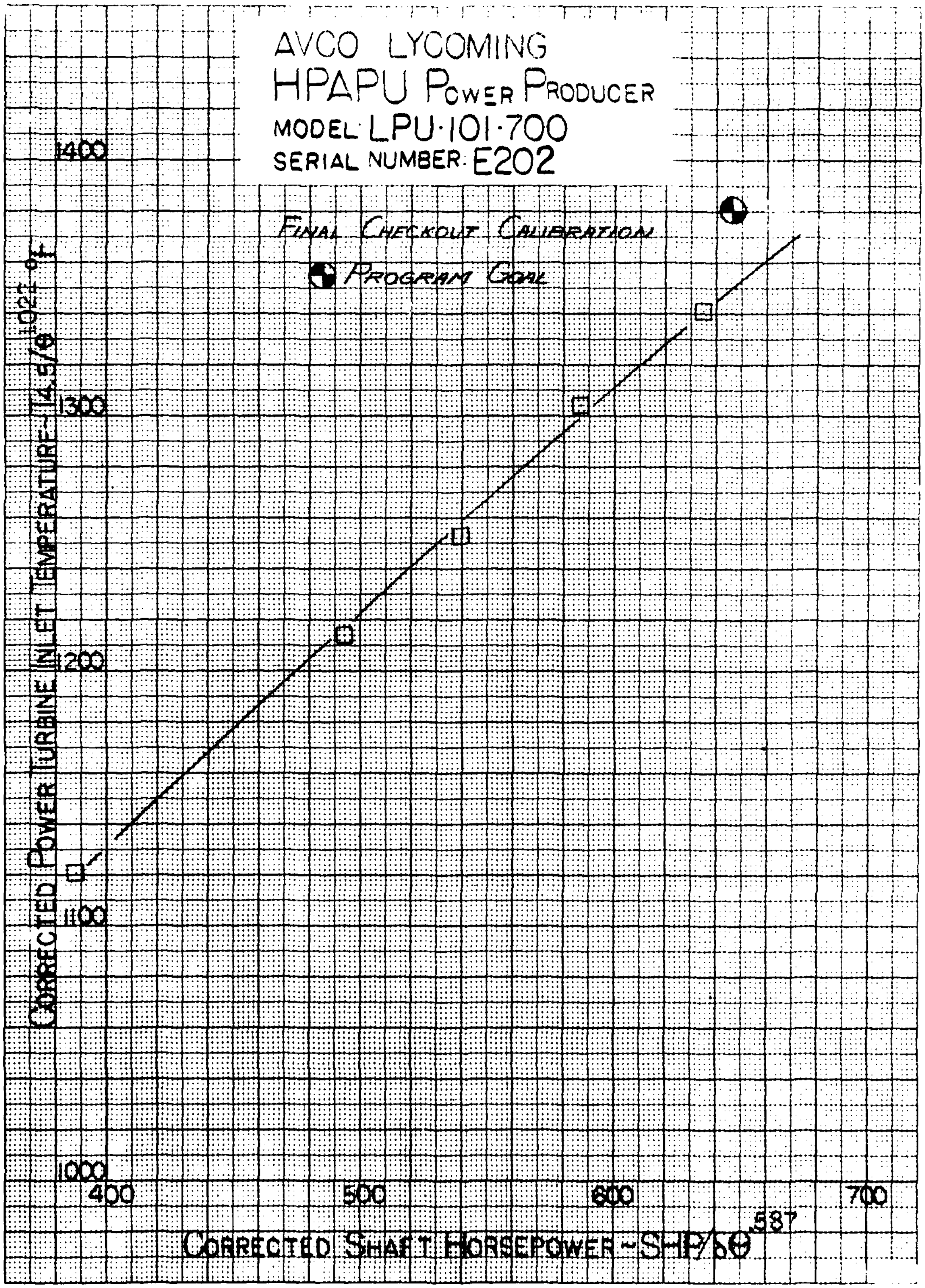

Figure 86. Final Checkout Calibration - Corrected Turbine Inlet Temperature Versus Corrected Shaft Horsepower, Engine S/N E202

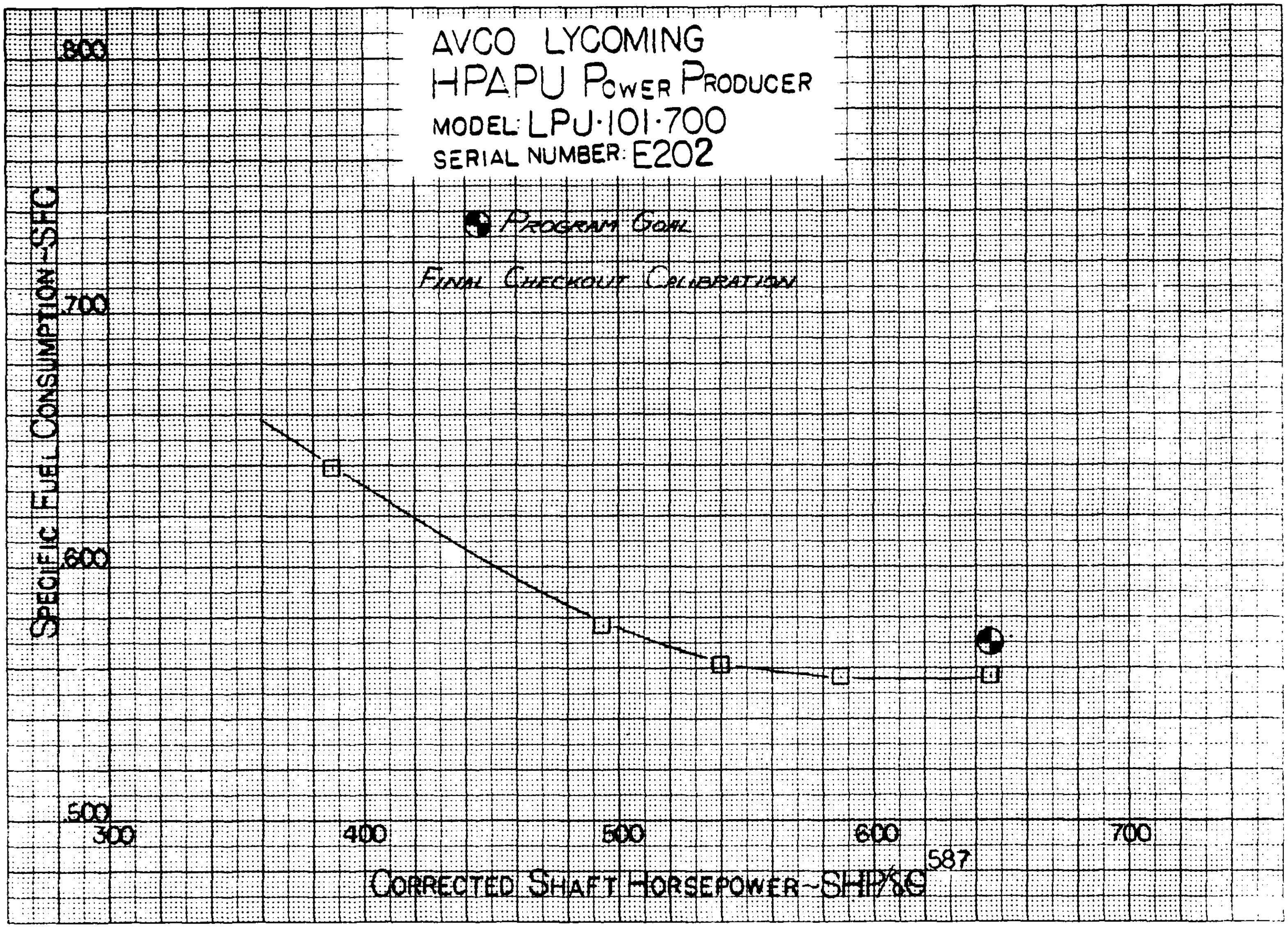

Figure 87. Final Checkout Calibration - Specific Fuel Consumption Versus Corrected Shaft Horsepower, Engine S/N E202

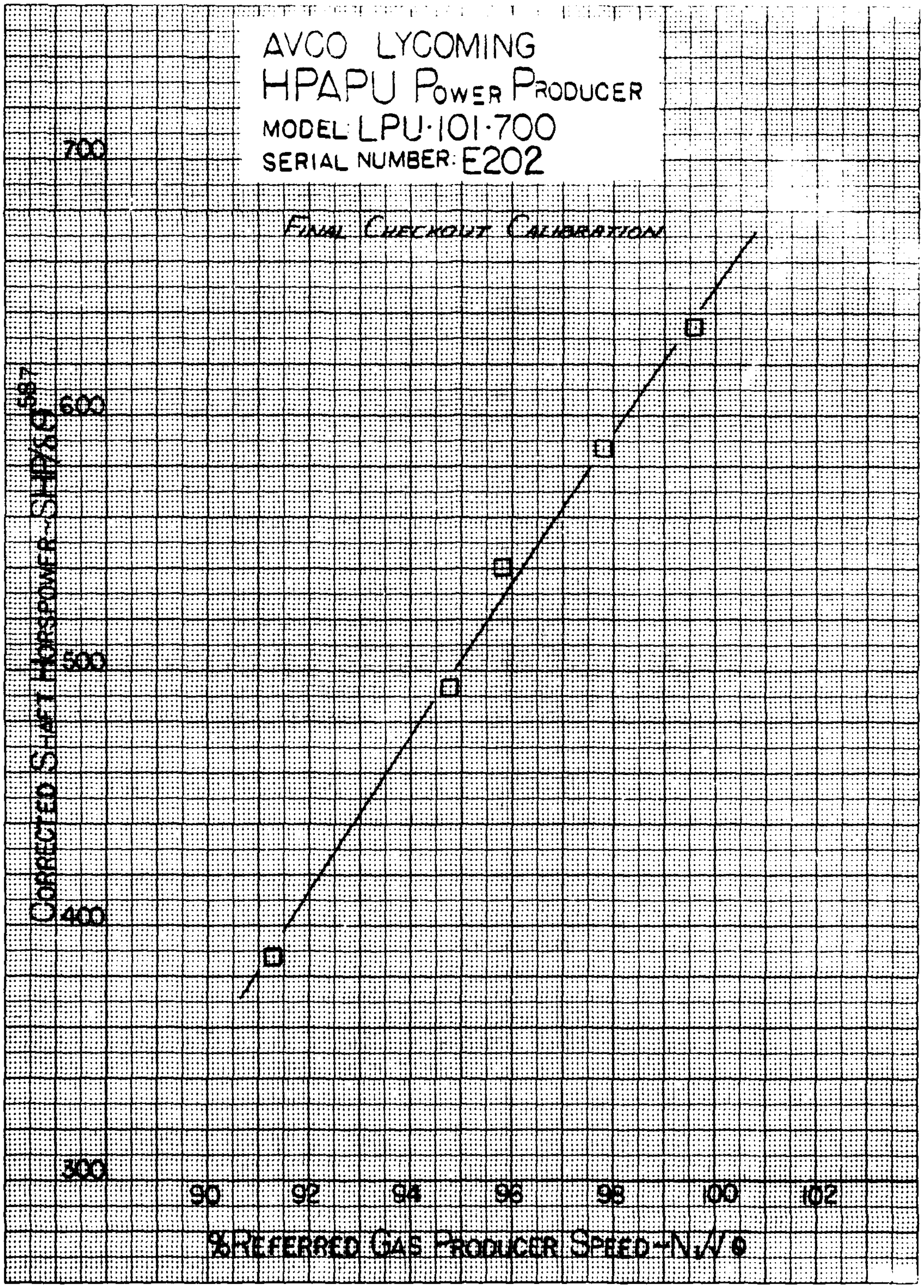

Figure 88. Final Checkout Calibration - Corrected Shaft Horsepower Versus Referred Gas Producer Speed, Engine S/N E202

SECTION V.

CONCLUSIONS

The high-performance auxiliary power unit demonstrator program met or exceeded all of the contractual performance requirements of the U.S. Air Force. The following tabulations outline program objectives and accomplishments for the power producer.

Rating at 130°F	Objective	Demonstrated
Output Power (shp)	200-500	456
Power/Volume Ratio (hp/ft^3)	130 (min)	182
Power/Weight Ratio (hp/lb)	1.70 (min)	2.43
Specific Fuel Consumption (lb/hp hr)	1.00 (max)	0.62

In addition to meeting the rating objectives, the power producer successfully completed rigorous environmental and endurance test programs. One power producer had to demonstrate satisfactory starting capabilities at sea level over a -65°F to +130°F temperature range and at altitude pressure and temperature conditions of 10,000, 20,000, and 25,000 feet. It was also required to operate at peak power for 10 hours at 130°F, and, when assembled to an HPAPU system, demonstrate 10 simulated main engine starts.

All requirements were demonstrated to at least the specified temperature range and, in the case of cold starting and peak powers, to -70°F and +135°F, respectively.

Environmental testing was conducted with the power producer assembled to a standard LTS 101 turboshaft gearbox, which used a Bendix pneumatic/mechanical fuel control. This arrangement worked at all conditions except 25,000 feet altitude, where a successful start was only accomplished by using a Bendix electronic test control. It can be concluded that in this application, fuel scheduling for starting is superior with electronic controls. Also, one of the engine ignitors and one of the fuel nozzles was found to be discrepant at the end of the program. This combination could well have contributed to the starting difficulties at altitude.

Endurance testing was conducted on a second power producer assembled to an HPAPU system. One hundred hours running time, consisting of 50 continuous hours (interrupted once for a facility wiring problem) at peak power and 50 cyclic hours, demonstrated the unit's basic durability.

Following successful completion of the test program, it can be concluded that the Avco Lycoming LPU 101-700 power producer satisfied all requirements of the Air Force Demonstrator Program and is recommended for incorporation into any future military APU application.

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